The GRAiNITA calorimeter

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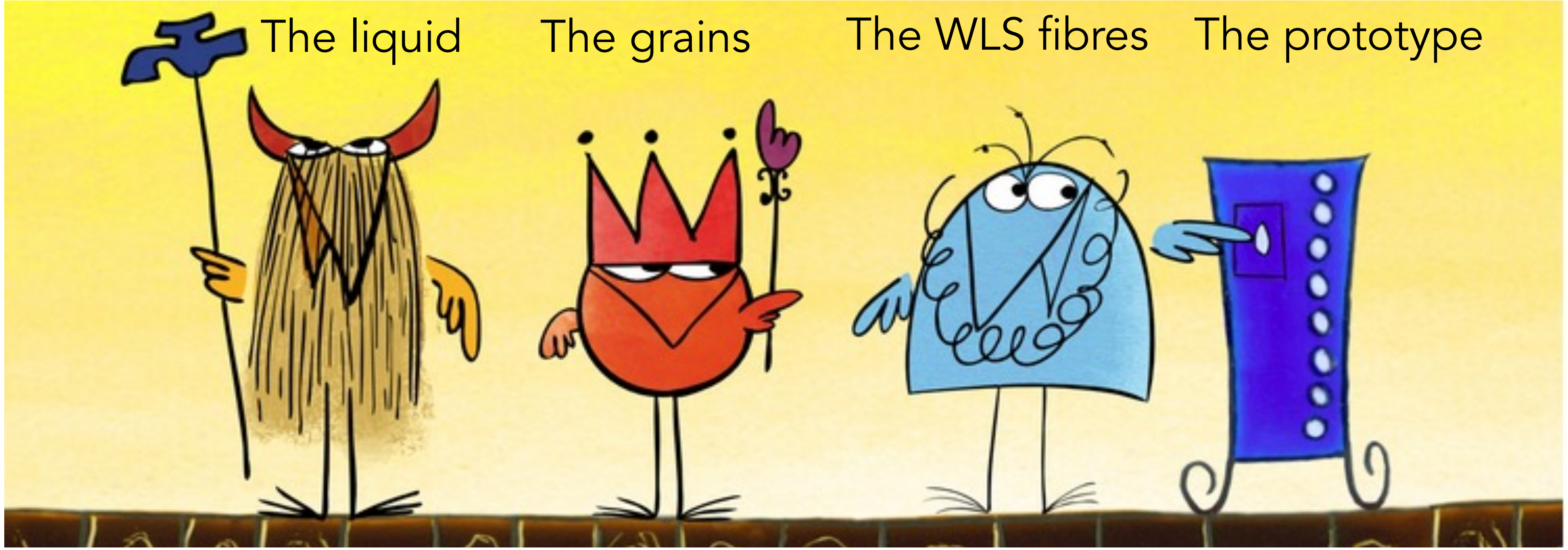
- The concept, the small prototype and the very first measurements

- First test beam results

- A word on pulse shape discrimination

The concept and the small prototype and the very first results



Ethylene glycol
- refractive index ~ 1.4

LST FastFloat
- density ~ 2.85 g/cm^3
- refractive index ~ 1.5

$ZnWO_4$

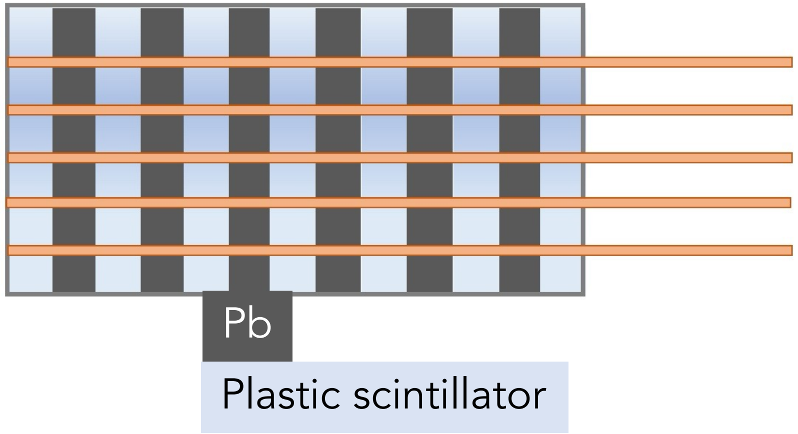
O2-(200) from Kuraray

The overall idea (in a nutshell)

Typical sampling calorimeters:

$$\frac{\sigma_E}{E} \sim \frac{10\%-15\%}{\sqrt{E}}$$

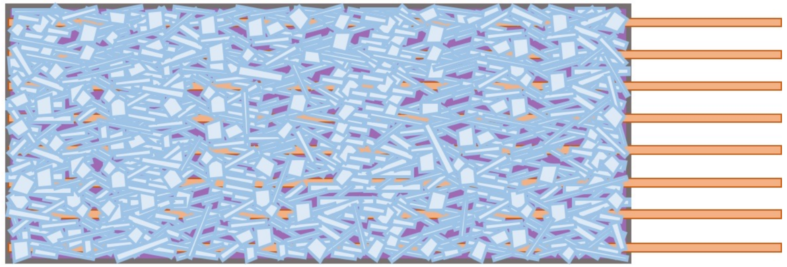
Shashlyk-type calorimeter



Requirements:

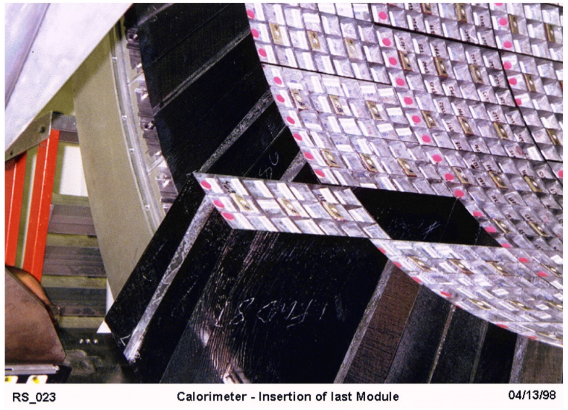
- Good energy resolution
- fine sampling
- scintillation light locally contained

GRAiNITA



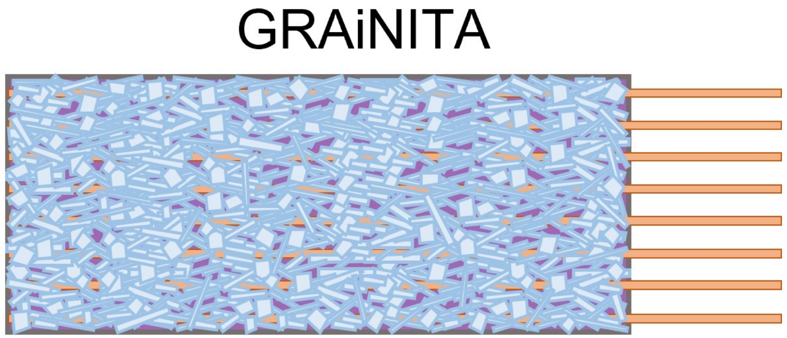
Crystal calorimeters :

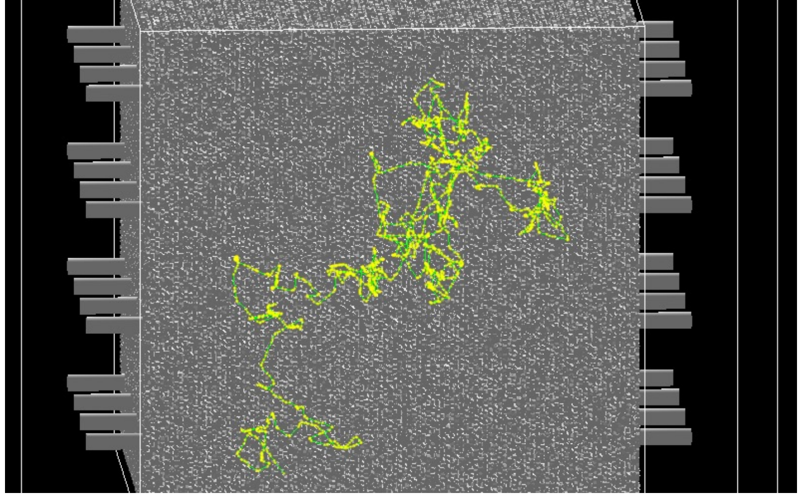
$$\frac{\sigma_E}{E} \sim \frac{1\%-2\%}{\sqrt{E}}$$



Main components :

- Scintillating grains
- WLS fibers
- Heavy liquid





Light is produced in the grains and collected by the WLS fibres

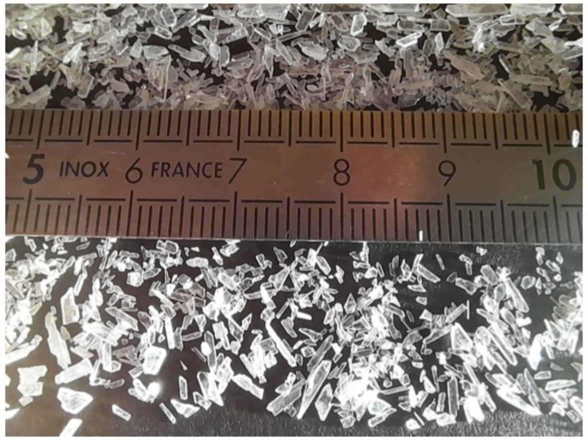
Choice of grains driven by number of photo-electrons and the production technique

The heavy liquid:

- eases the light collection by the WLS (index of HL as close as possible to the index of grains)
- increases the density and thus reduce the size of the calorimeter

$ZnWO_4$ has been identified as a promising candidate

	BGO	$ZnWO_4$
Effective Z	74	61
Density (g/cm^3)	7.13	7.87
Refractive index	2.15	2.0 - 2.3
Light yield (photons/MeV)	~ 9000	~ 9000
Peak emission wavelength (nm)	480	480
Decay time (μs)	0.3	20
Radiation length (cm)	1.12	1.20
Molière radius (cm)	2.26	1.98

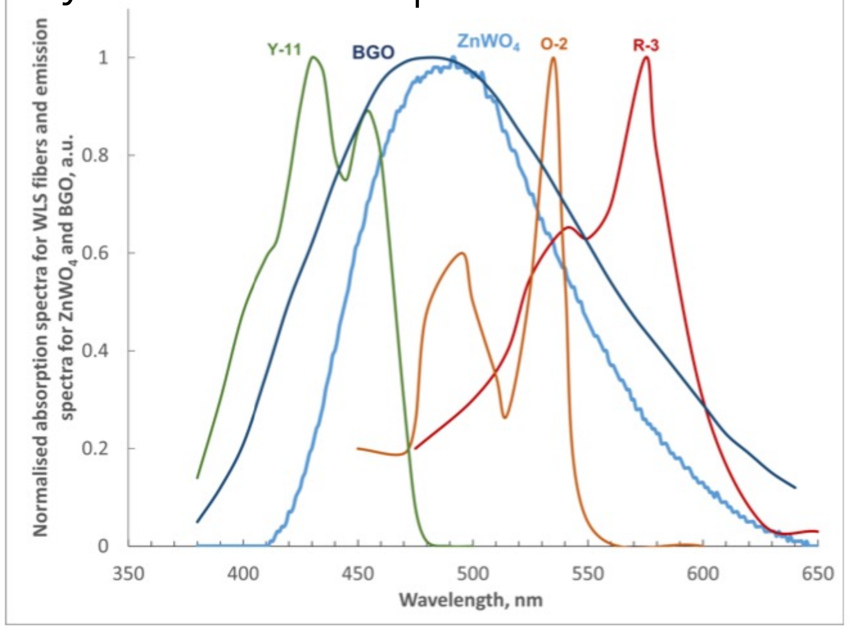


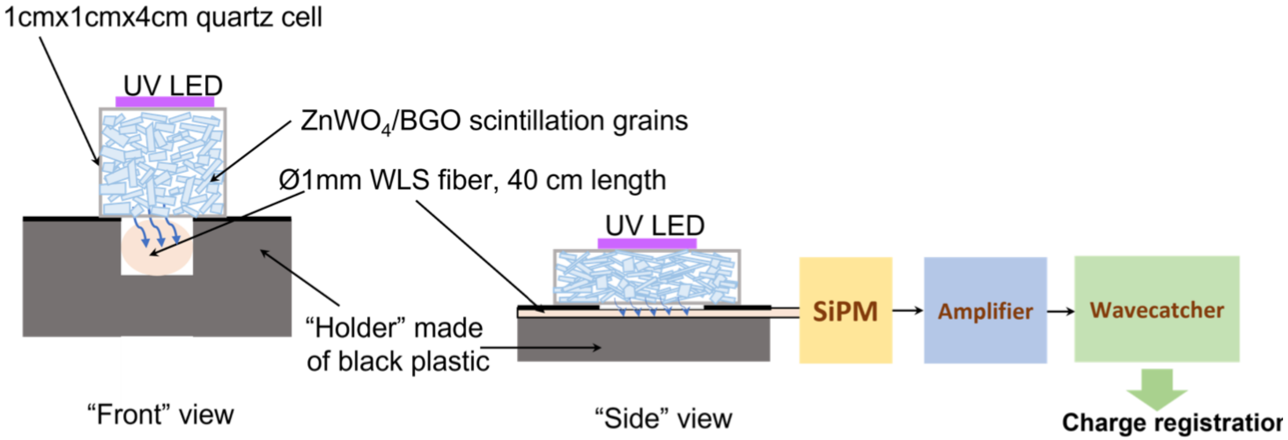
Scintillation decay time ok for FCC-ee (~50 kHz at the Z pole).

ISMA: dedicated R&D to produce ZnWO4 grains with the flux method (cost effective). Production technique mastered.

~ 1 kg of high-quality $ZnWO_4$ grains produced

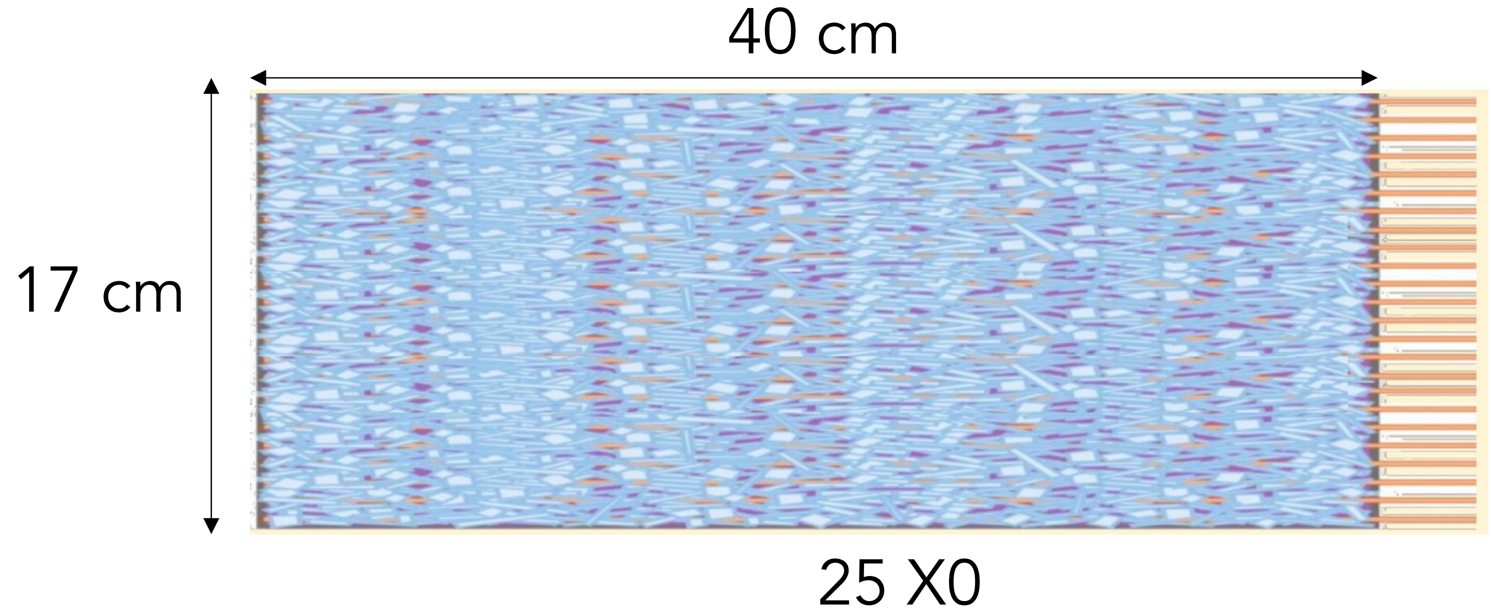
Absorption spectra for Y-11, O-2 and R-3 fibers from Kuraray and emission spectra for BGO and $ZnWO_4$





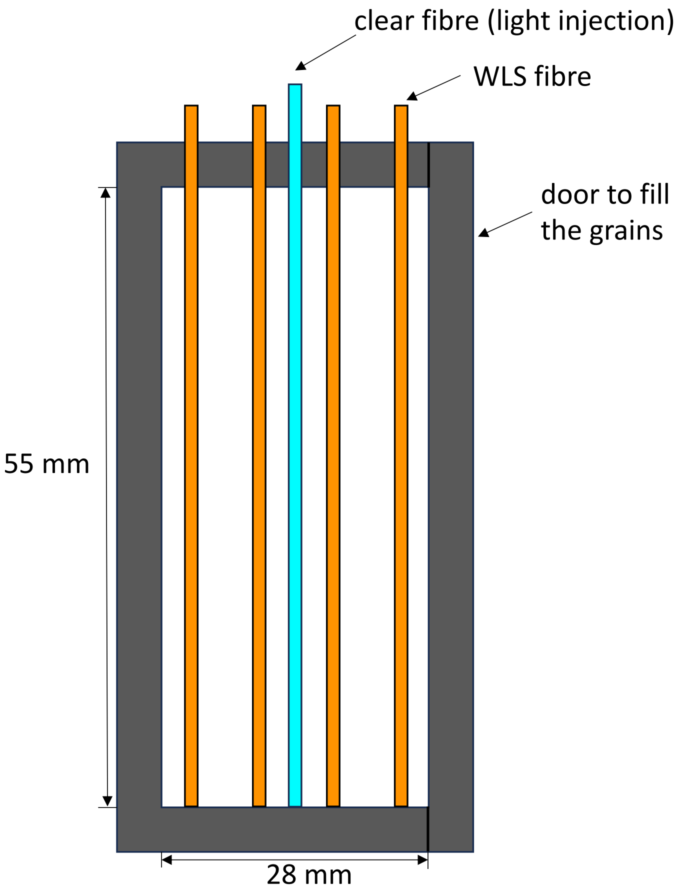
	Relative efficiency (%)		
Fiber type	$ZnWO_4$ grains (~ 9 mm)	BGO grains (~ 9 mm)	
O-3(300)	100	100	ref
O-2(200)	104	104	preferred choice
Y-11(200)	44	98	
R-3(100)	60	n.a.	

Goal: scale one module to contain the shower of a 25 GeV photon

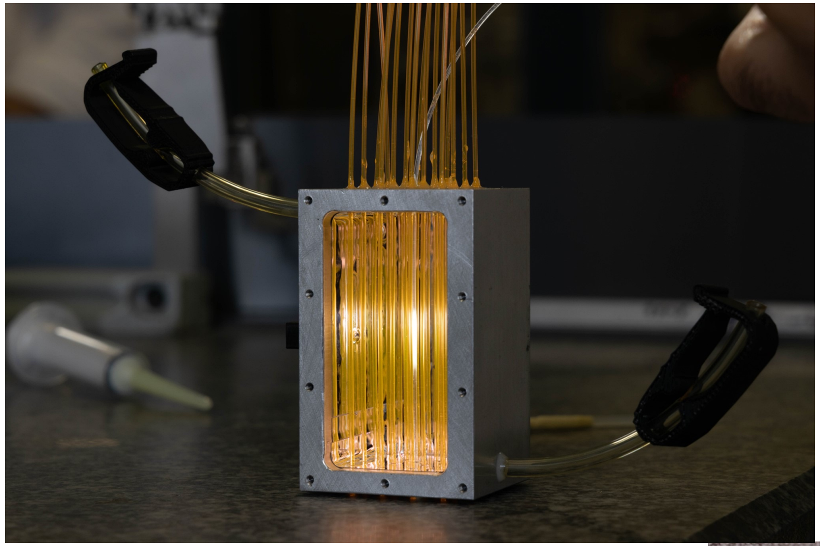


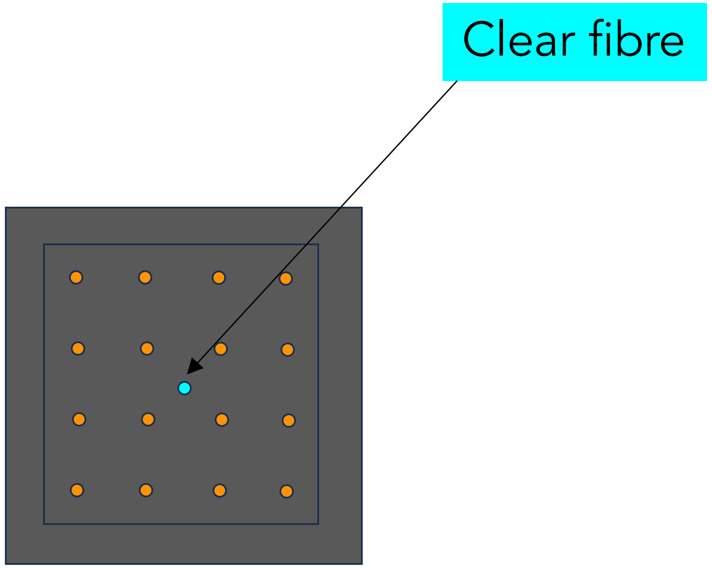
~50 kg of grains

But it started small

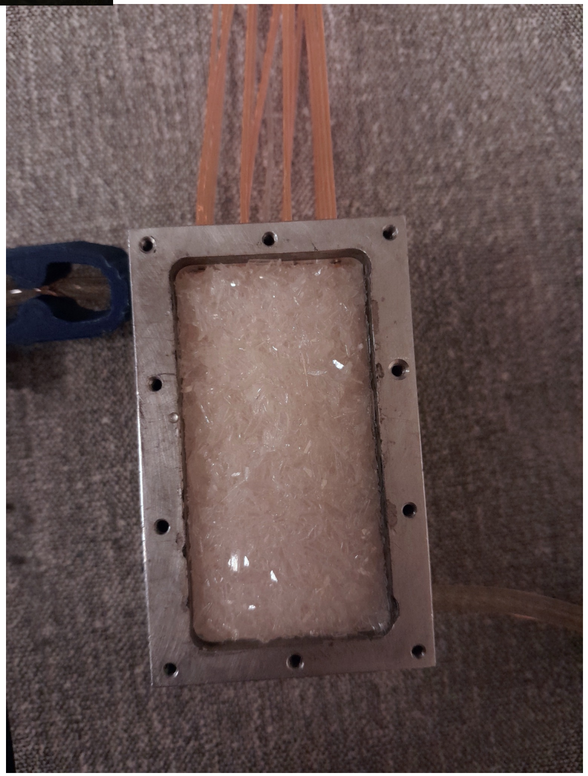


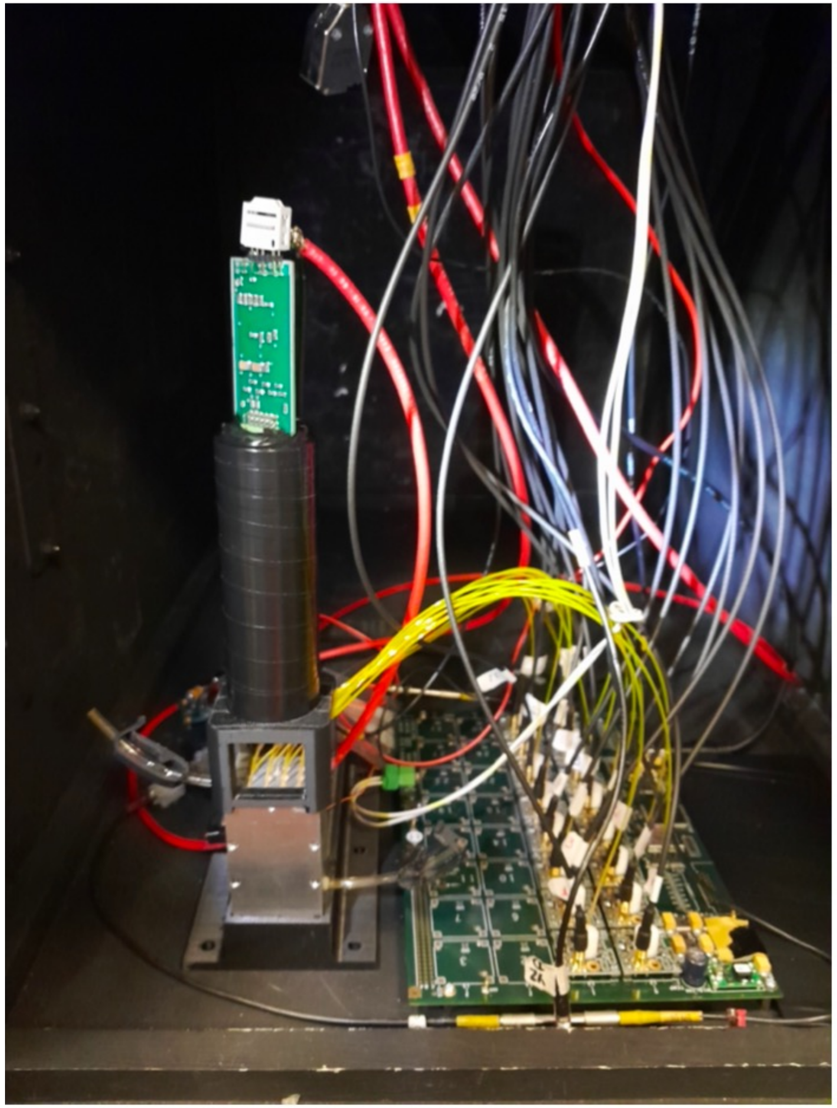
Side view





top view





16 WLS fibres couples to a SIPM mounted on a PCB for amplification.

Signals are digitized at 3.2 GHz with a Wave Catcher.

The photo-electrons are identified and counted in a 25 μs window.

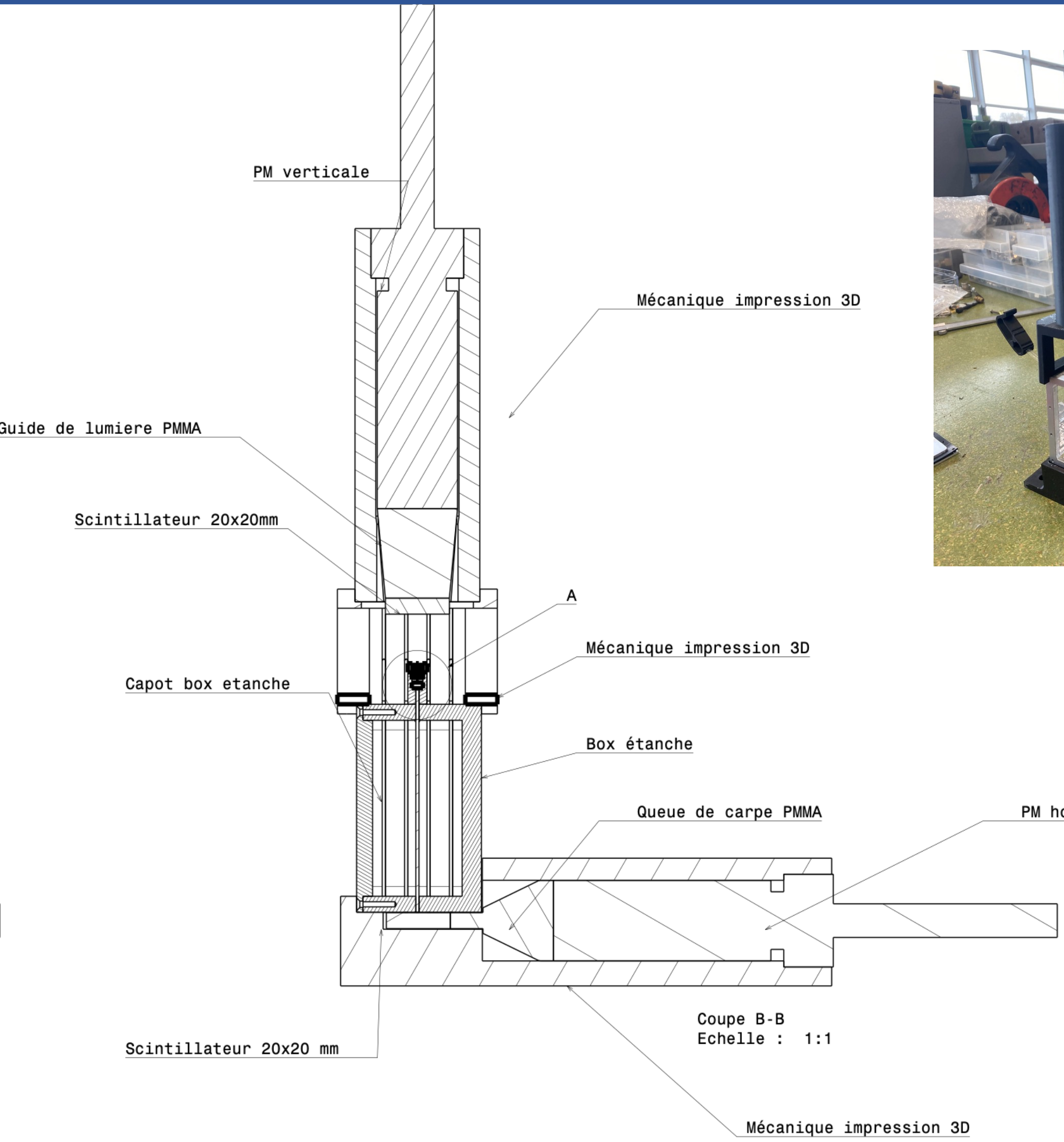
First measurements

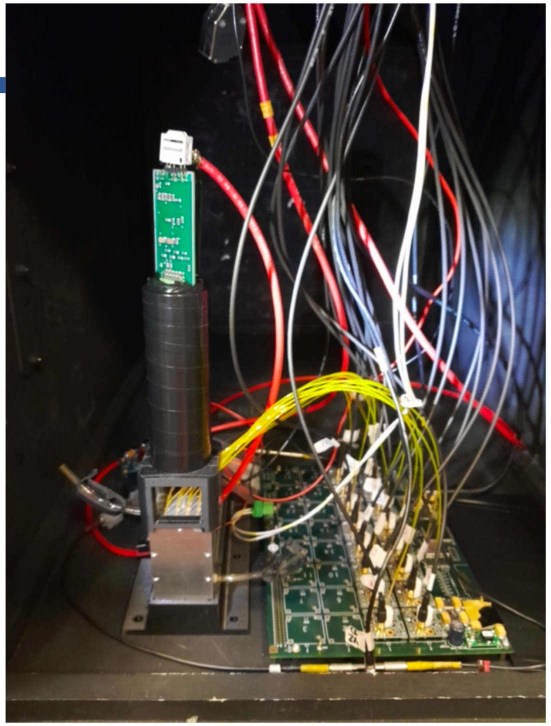
stochastic
(dom. at high E)

calib.,
non uniformity

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Cosmic rays test bench



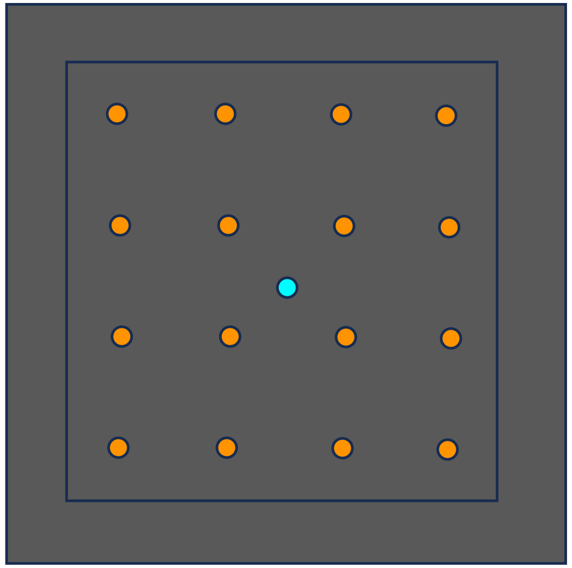


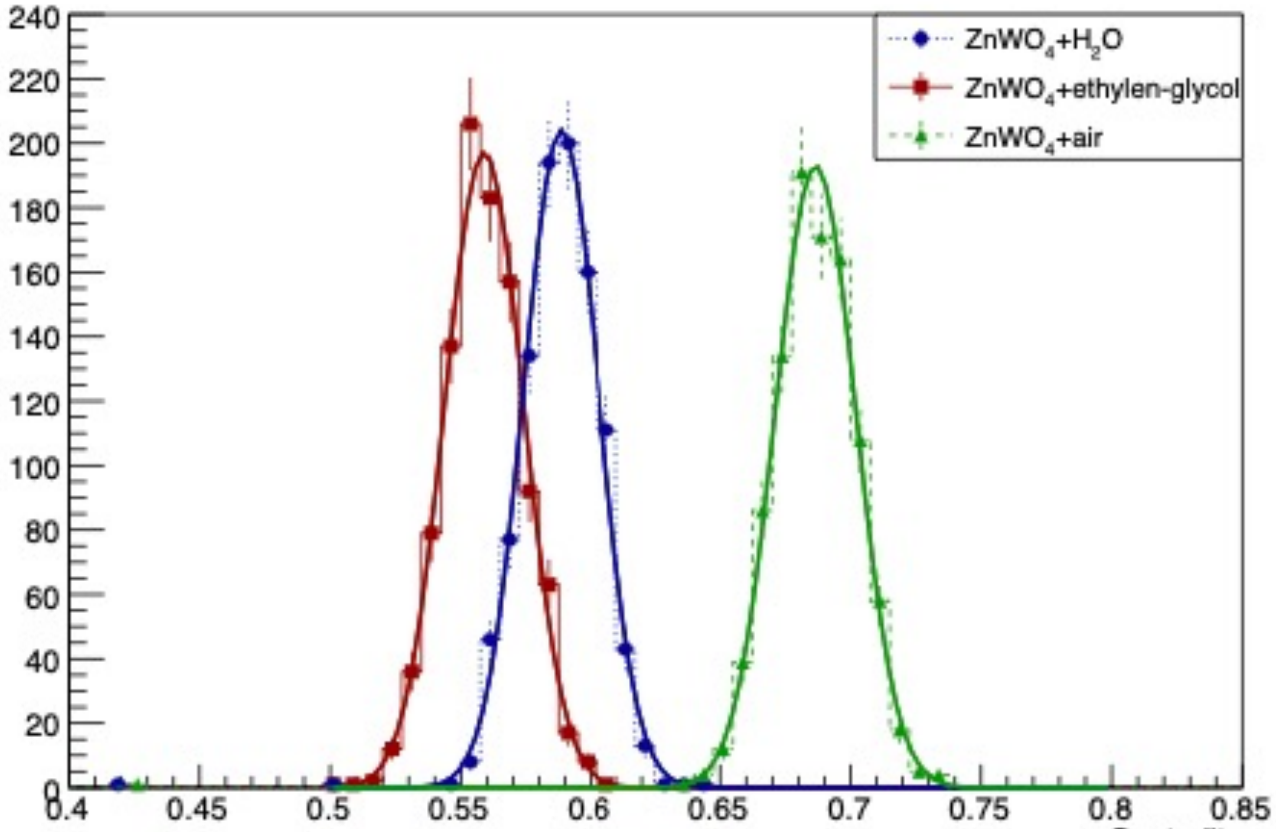
Small (2 x 2 x 5.5 cm^3) prototype

~ 1 week to record 500 events
Energy deposit ~ 40 MeV

First results using the green LED light injection

JINST 19 P04008





$ZnWO_4$

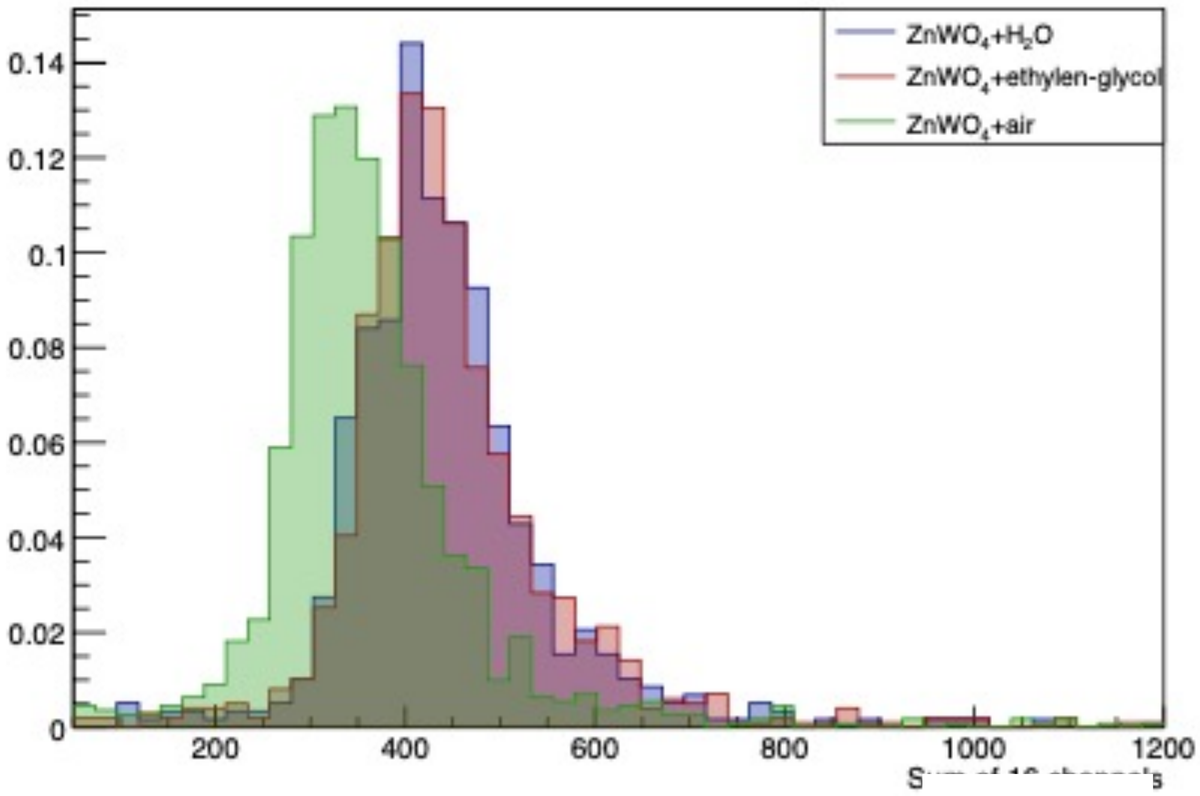
$ZnWO_4$ + H_2O

$ZnWO_4$ + EGL

$$\text{Centrality} = \frac{4\ central\ channels}{Sum}$$

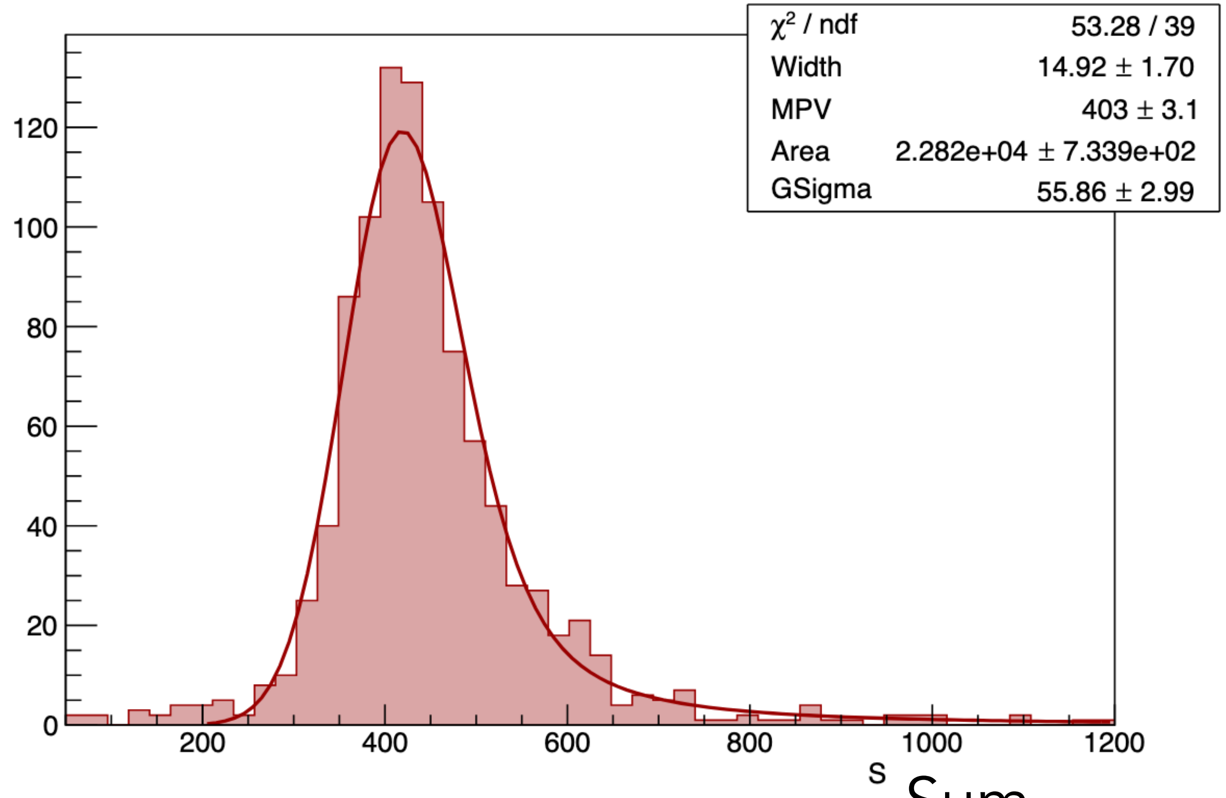
Light is confined

With cosmic muons:



Sum

Landau fit



Sum

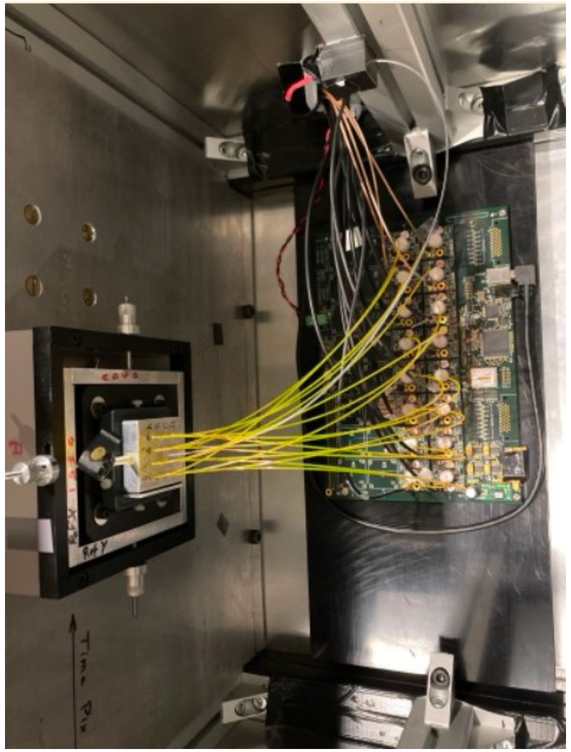
⇒ ~ 10 000 photo-electrons/GeV

⇒ opens the road to a a statistical fluctuation of $\frac{\sim 2\%}{\sqrt{E}}$ due to photon statistics

Term smaller than usual sampling calorimeter because of small grains and high density of scintillator

First test beam results

arxiv:2512.03811 (submitted to JINST)



Main objective: investigate the uniformity response (constant term in the energy resolution)

Which data ?

2 days of data-taking (in the shadow of LHCb PicoCal test in June 2024):

- ~ 2 millions of muons events
- ~ 48 millions of pions events (small prototype: only 20% of pions are interacting)

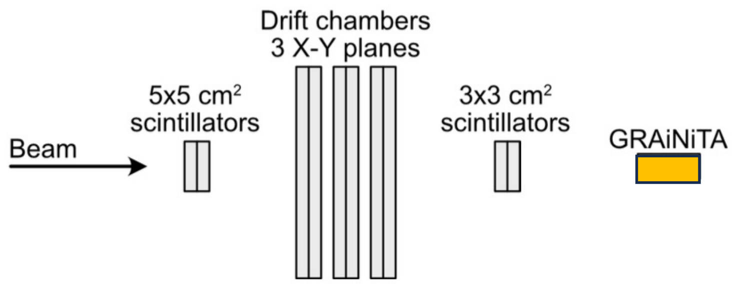
Energy ~ few 10 GeV

2 data-taking periods:

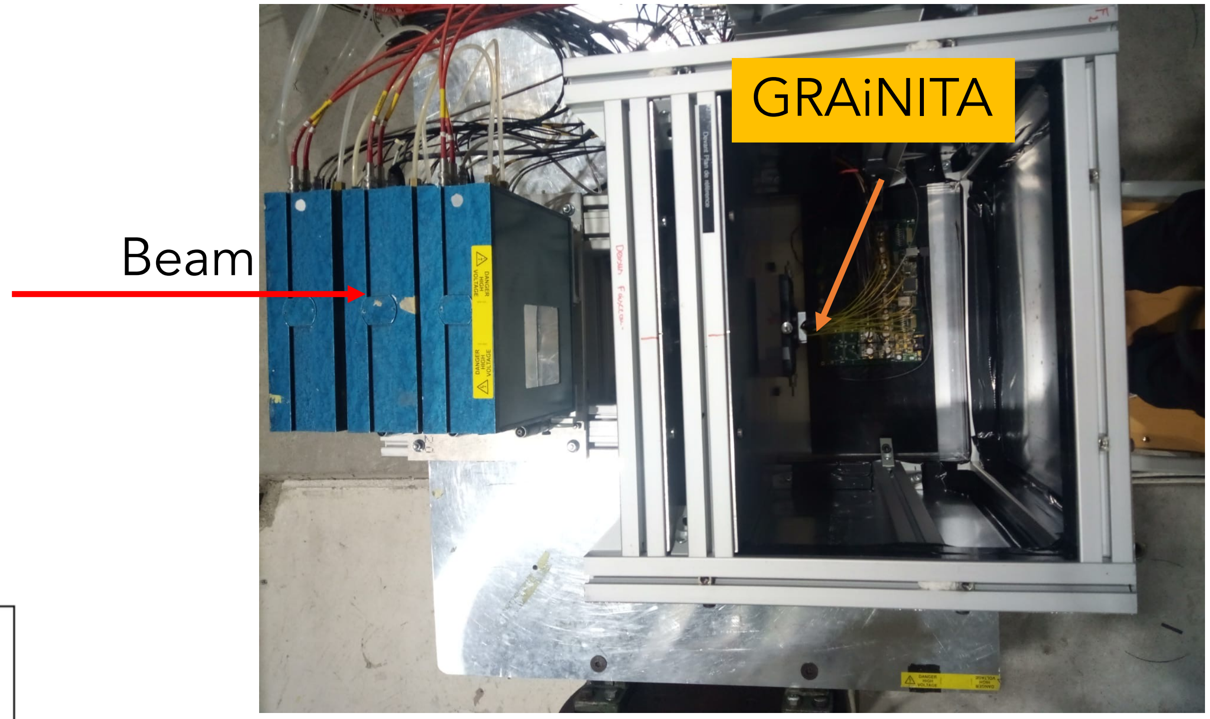
- $ZnWO_4$ grains in water
- $ZnWO_4$ grains in water-based sodium polytungstate solution (*Fastfloat*)

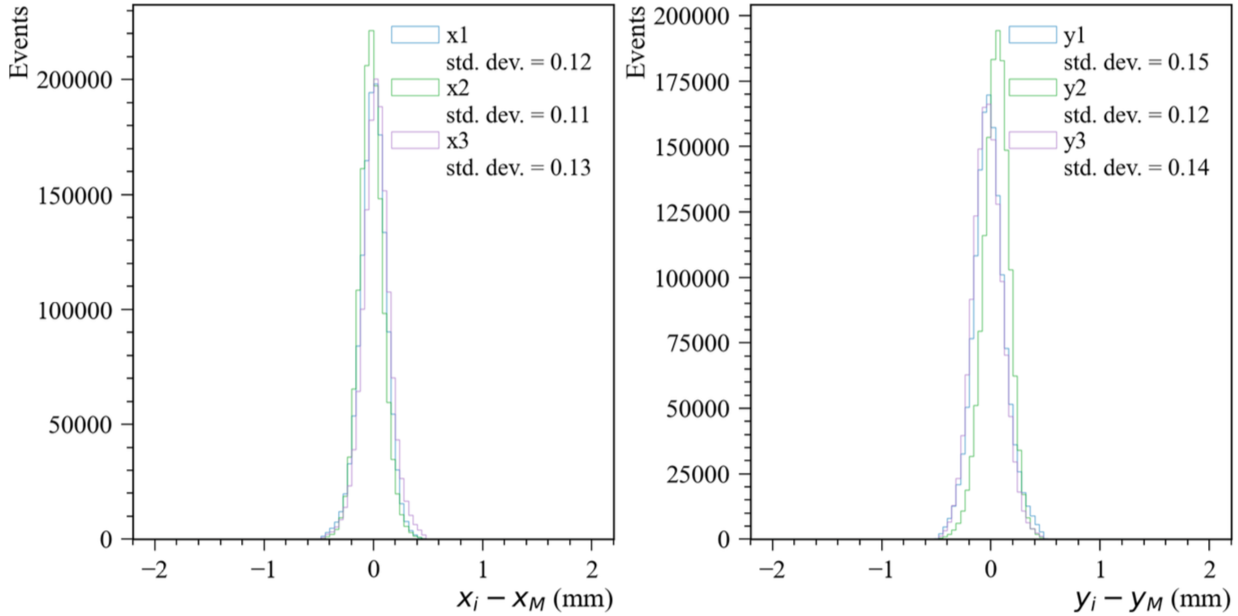
(refractive index = 1.5,
density = 2.85 $g.cm^{-3}$)

Set-up



GRAiNITA read-out triggered by the drift chamber + scintillators





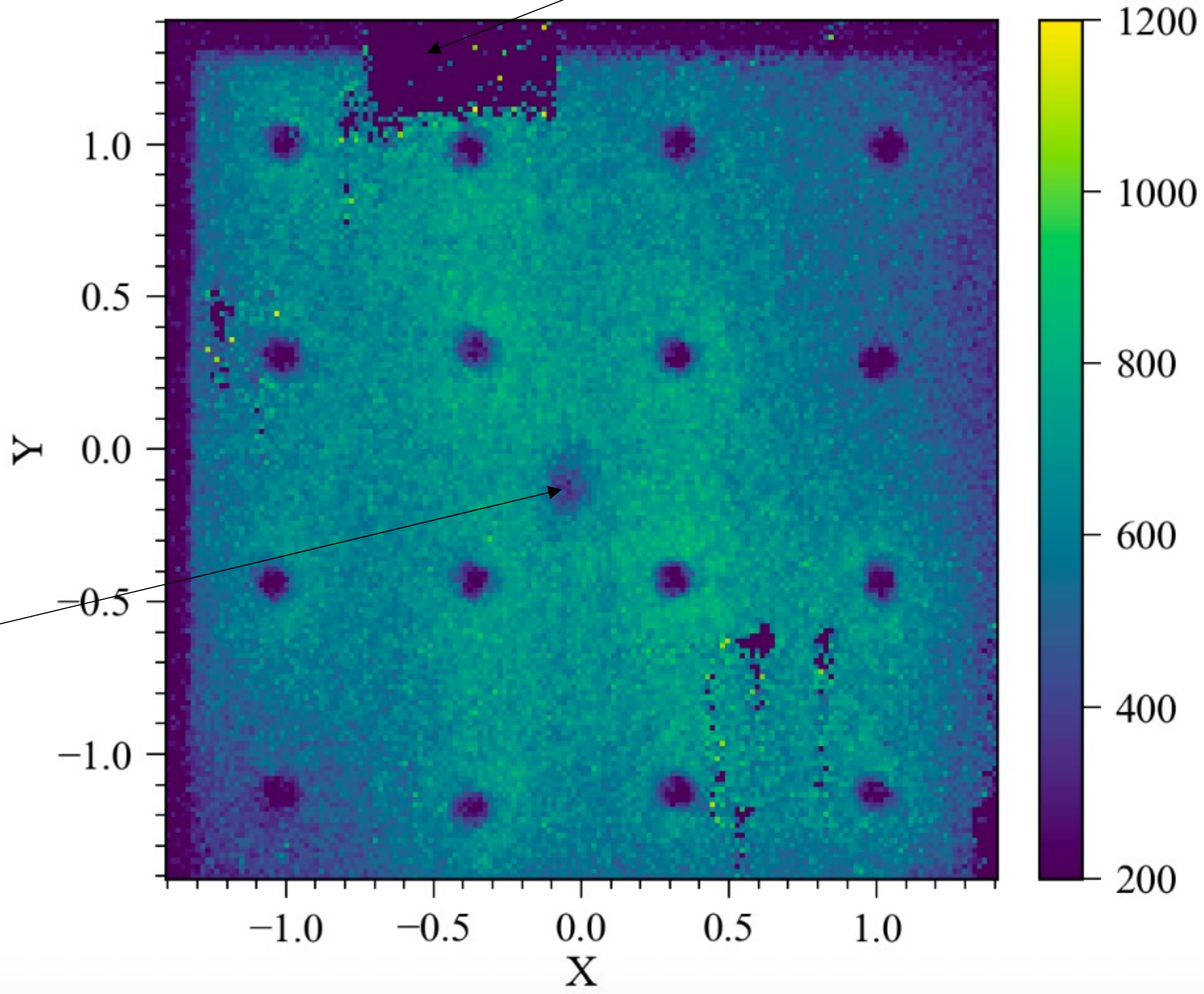
Resolution on the track position ~ 170 μm

A very first look in 170x170 μm^2 bins

DWC not fully functional

for muon tracks in each bin:
mean value of N_{PHE} from the sum of the 16 WLS fibres

Clear fibre is bent

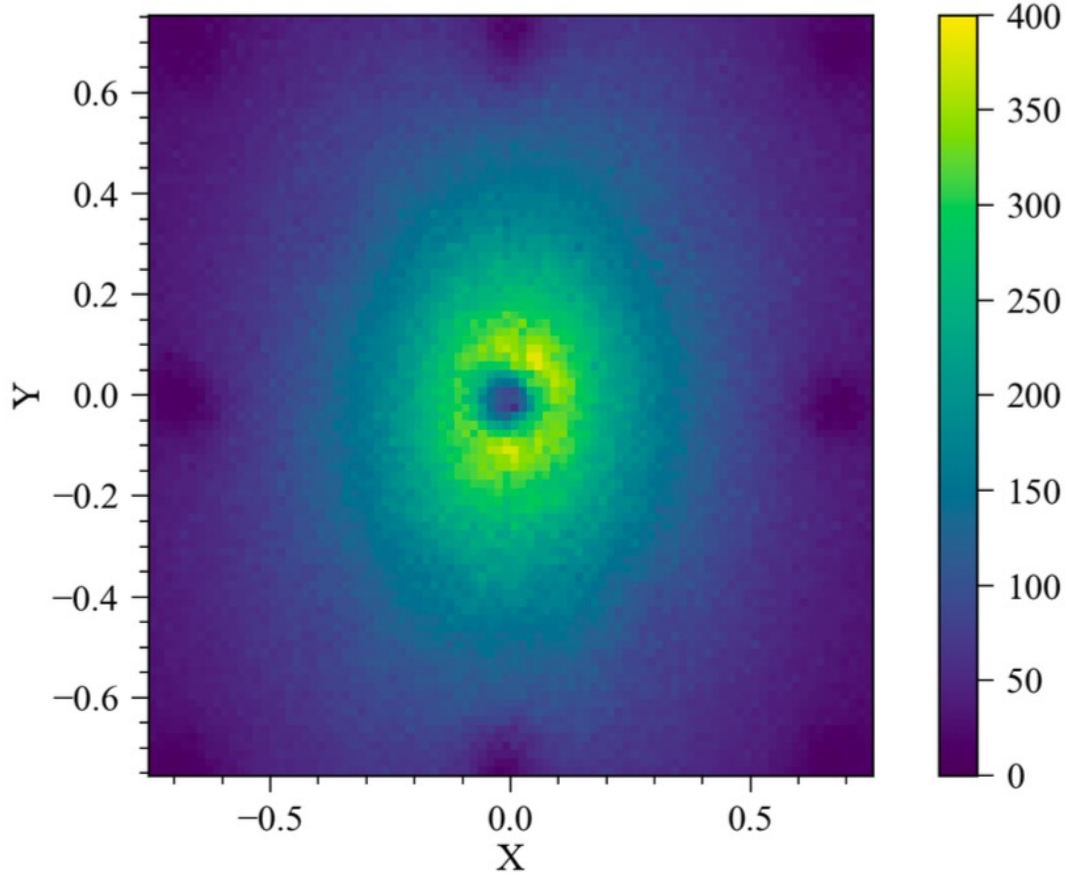


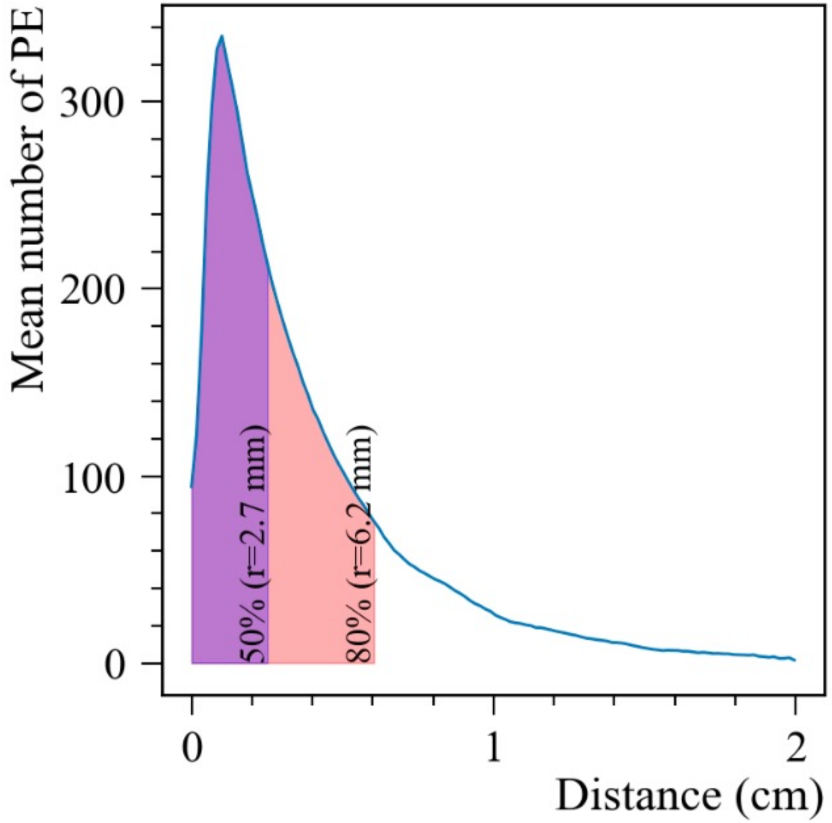
Light confinement

confirmed

Using muons and the 4 more central fibres

Signal on a given fibre as a function of the position of the track

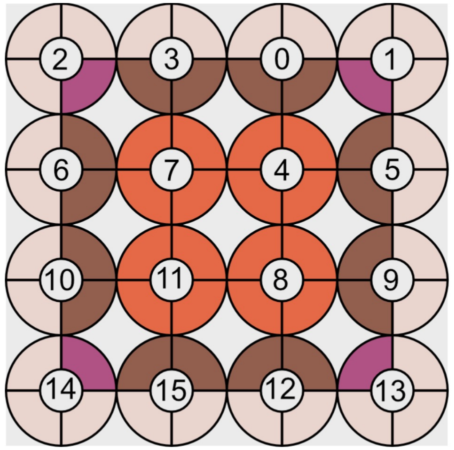


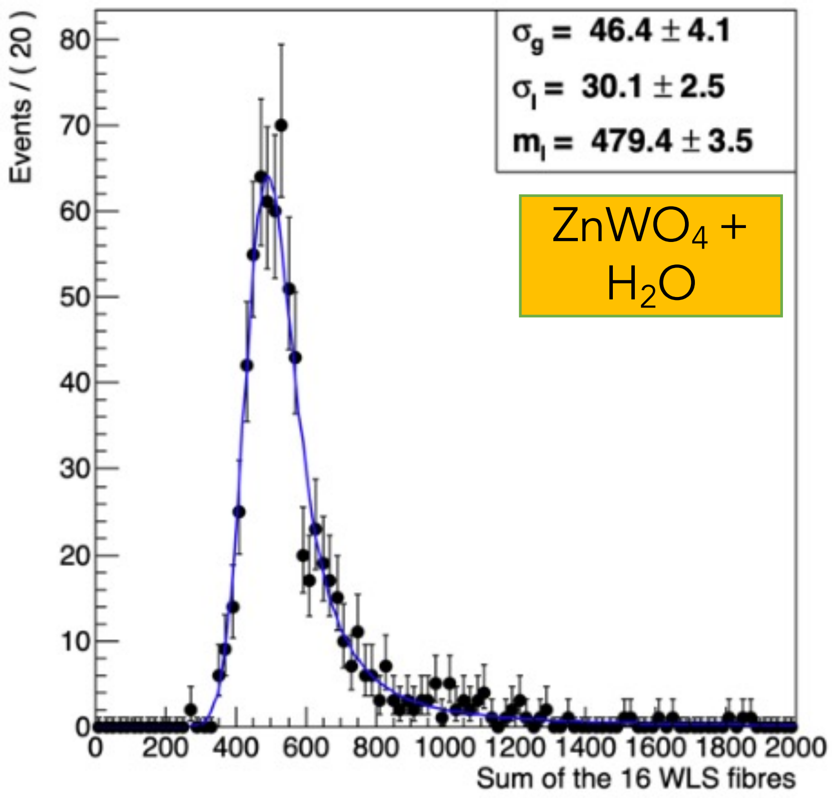


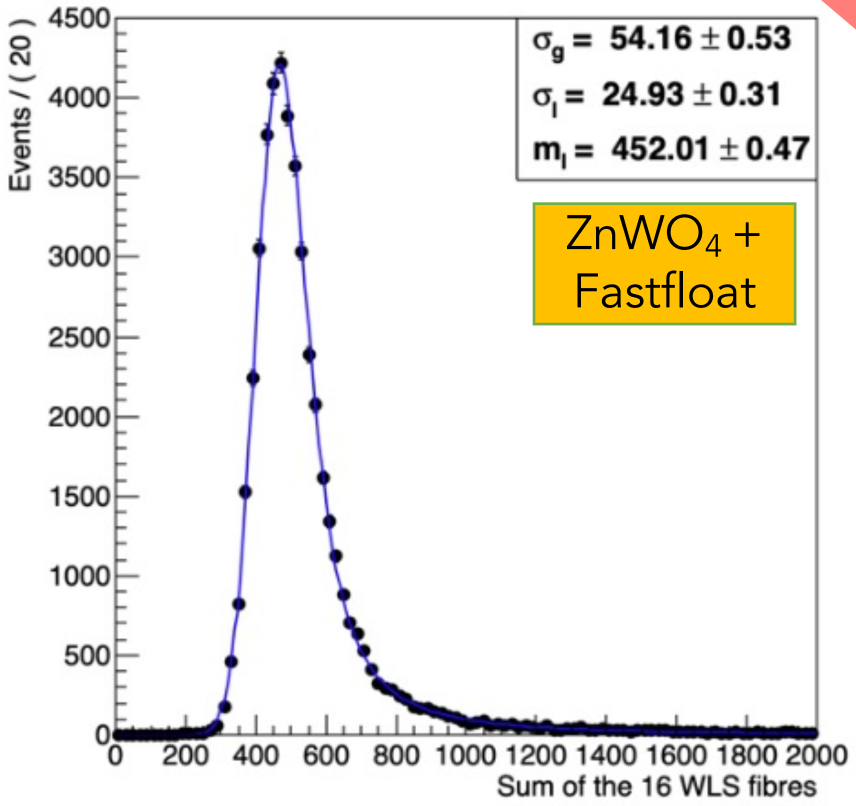
Stochastic term

confirmed

Use muon tracks close to the centre (orange zone)







Test of the uniformity

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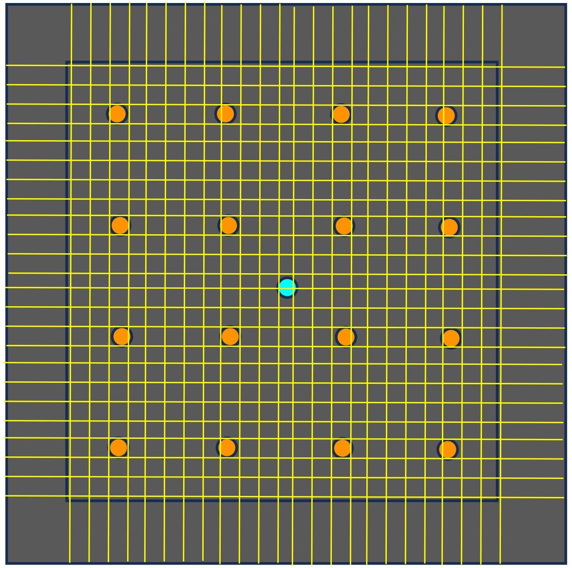
Pave the prototype surface by bins of 1 mm^2
Measure the sum of the 16 WLS signals for each bin
Fit the integral to extract the most probable value



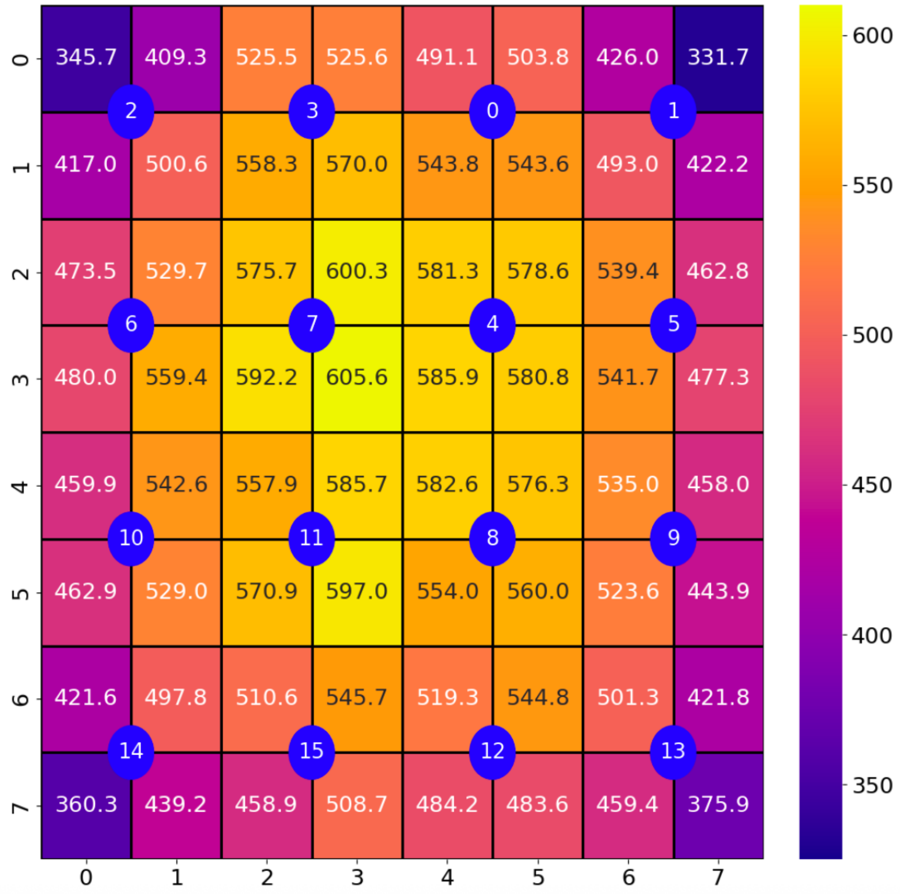
Challenges:

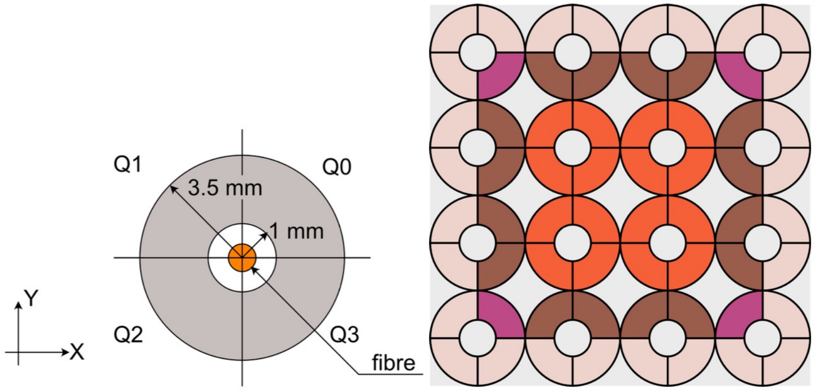
- very large data samples required
- with such a small prototype, the handling of the border effects is intricate to mitigate.
- data-taking issues (liquid leakages + electronics configuration problems etc…)

Data processing for non-uniformity assessment

Prototype plugged and un-plungged many times during the beam test period
→ need for homogenised responses

Muon hit map after the homogenisation:

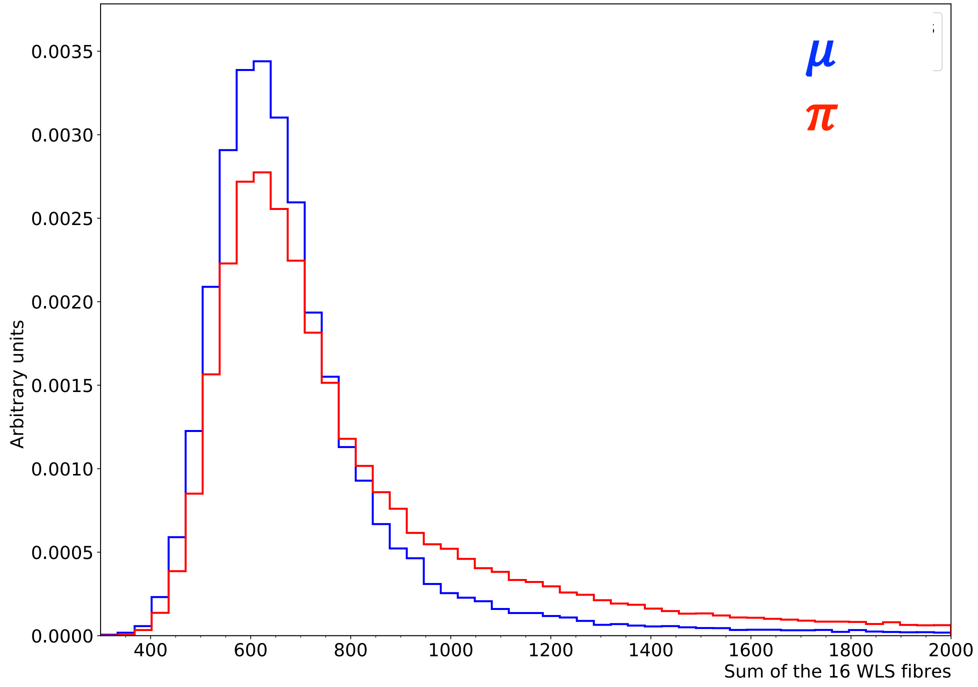




→ Fiducial cuts to be applied despite the VM2000 on the walls.

→ Pion runs to be used (larger stat)

Pion fitting model



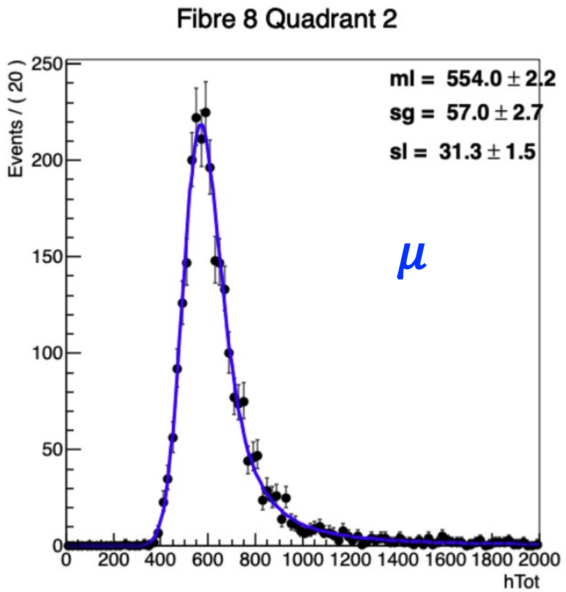
μ **Muon** signal : Landau⊗ Gauss (M(s))

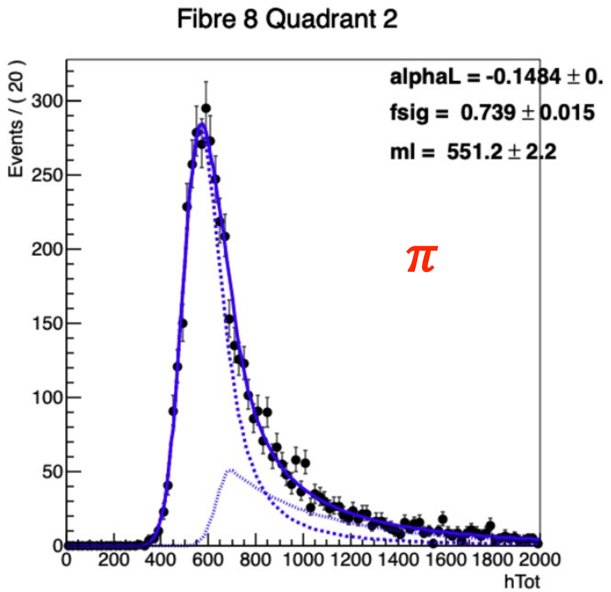
Pion Signal P(s) = f_{sig} M(s) + (1- f_{sig}) CB(s)

$\sigma_{CB} = \sigma_G$

$n_L = 6$

$x_{0CB} = 8/9 \sqrt{2}\, m_L$





Fit all fibres separately and extract all nuisance parameters

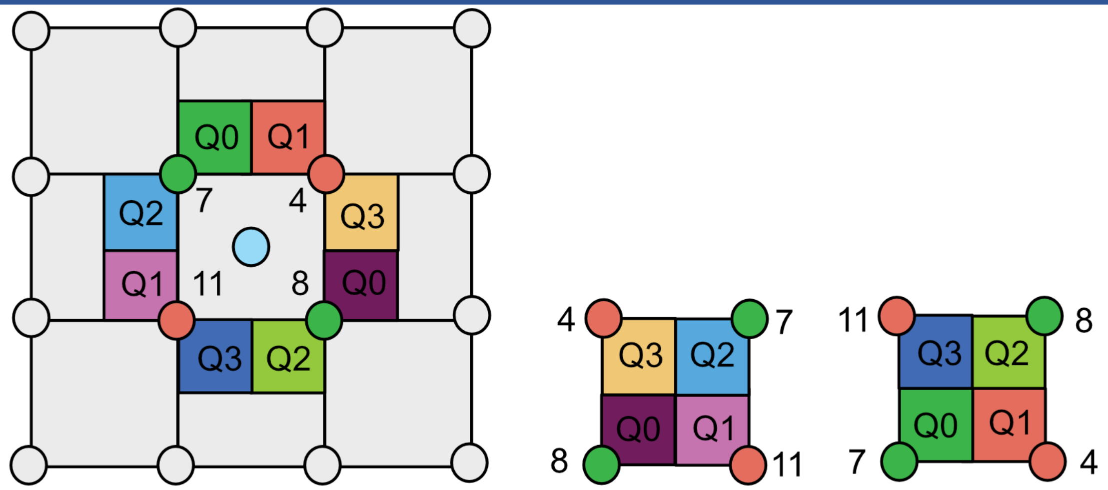
Fix to the mean value of the nuisances parameters

→ one free parameter : the Landau mean

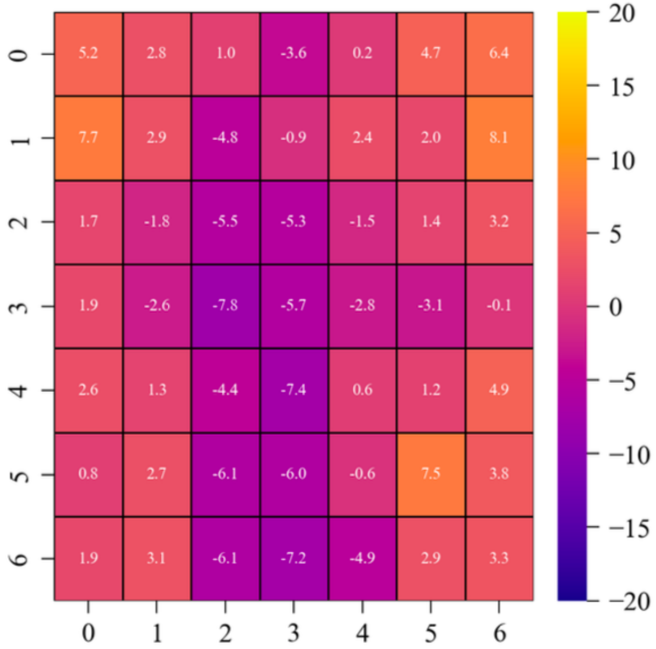
σ_l	σ_g	f_{sig}	α_L
19.7	49.6	0.736	-0.126

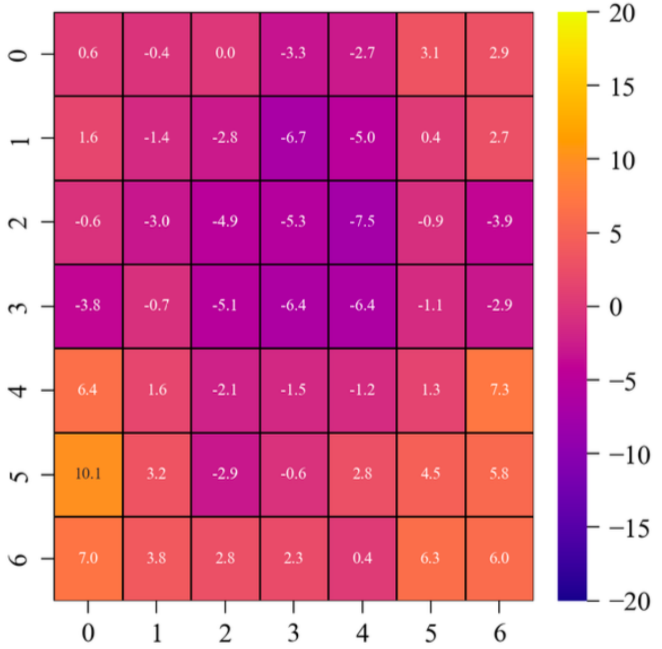
Method tested one and applied to the 15 others !

Avoiding the walls and the clear fibre



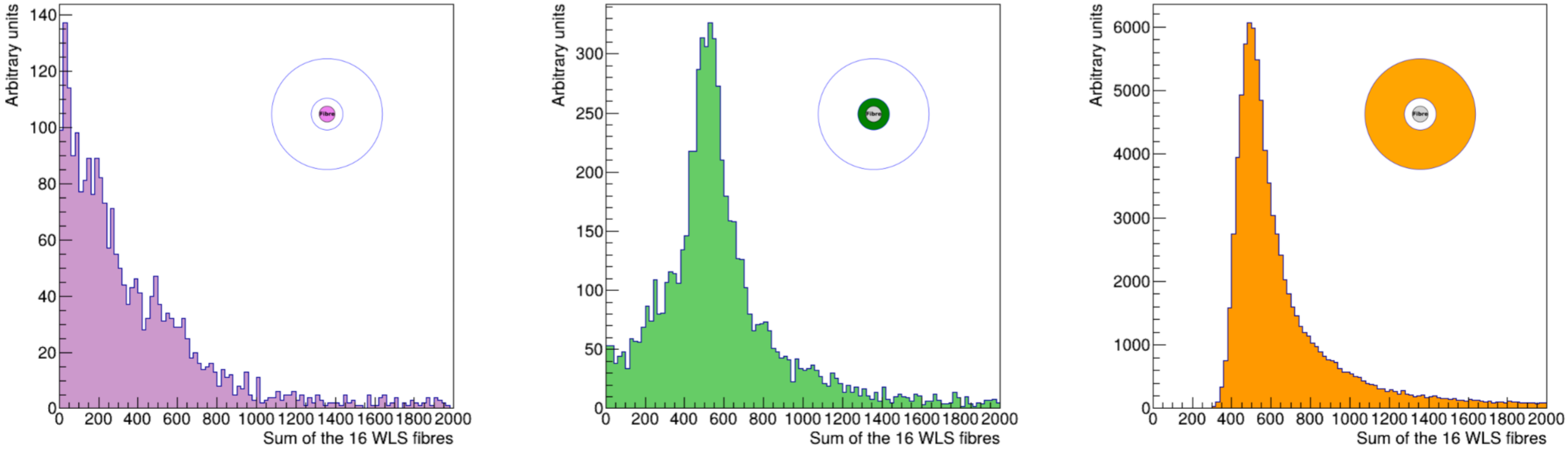
Pions hit map (1 mm^2) on the virtual units fractional values (%)





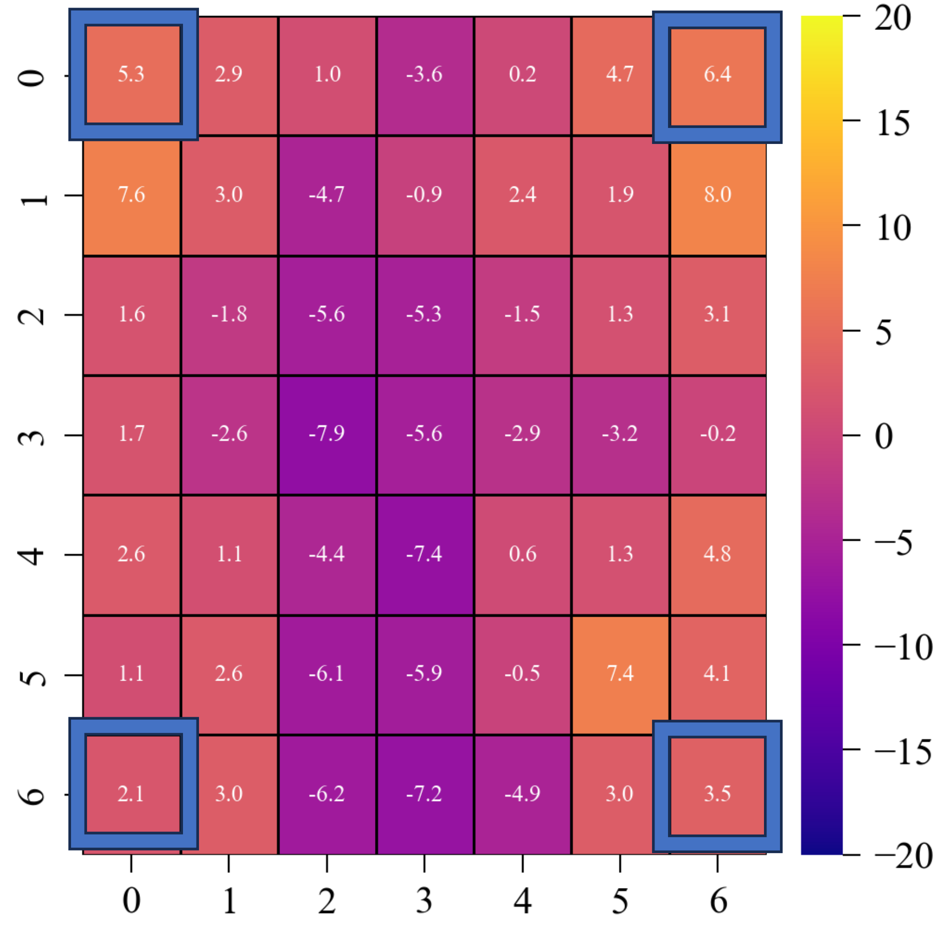
Rms variation of signal over different positions less than 10%

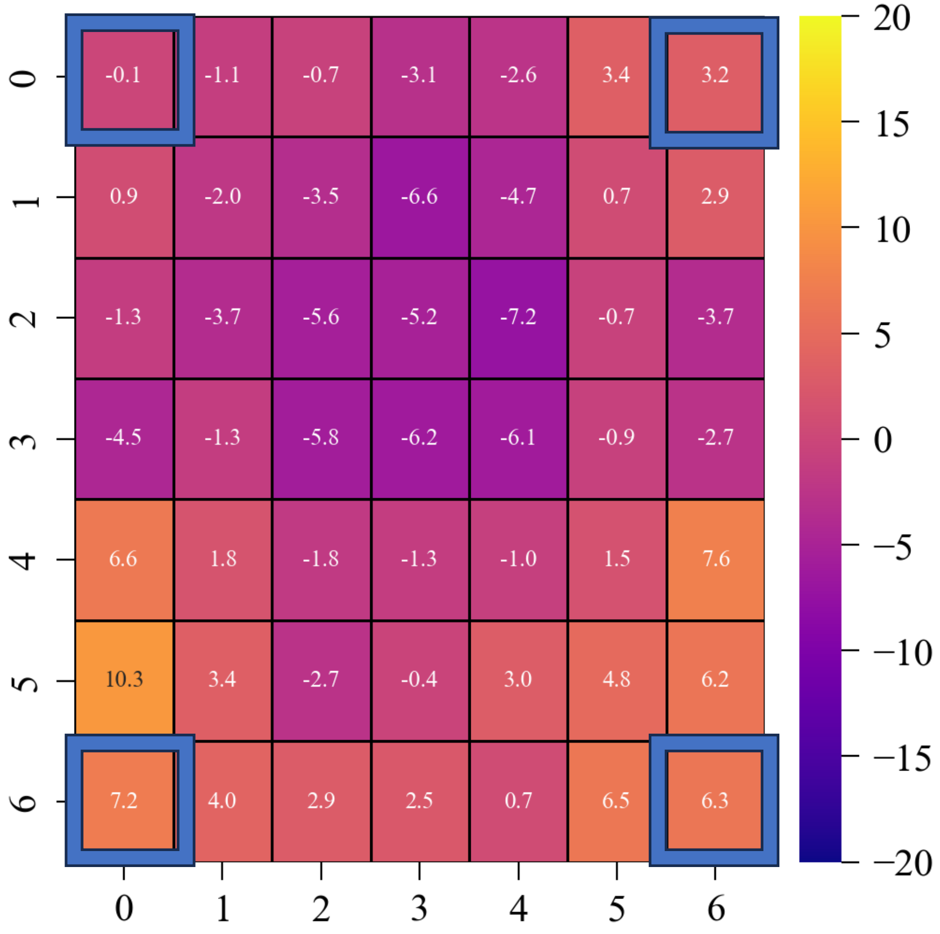
As expected signal varies a lot if the track hits the fibre



In the simulation when a track hits a fibre, no scintillation light is emitted

Hitmaps fort the 2 virtual units (in %)



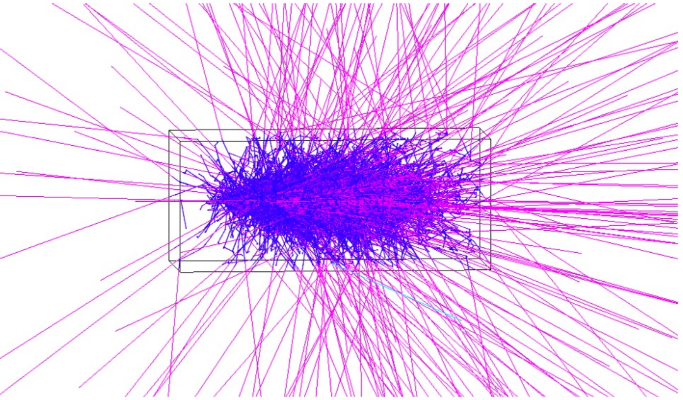


Bin where there is a fibre. Mean replaced by average of adjacent bins.
In the simulation when a track hits a fibre, no scintillation light is emitted

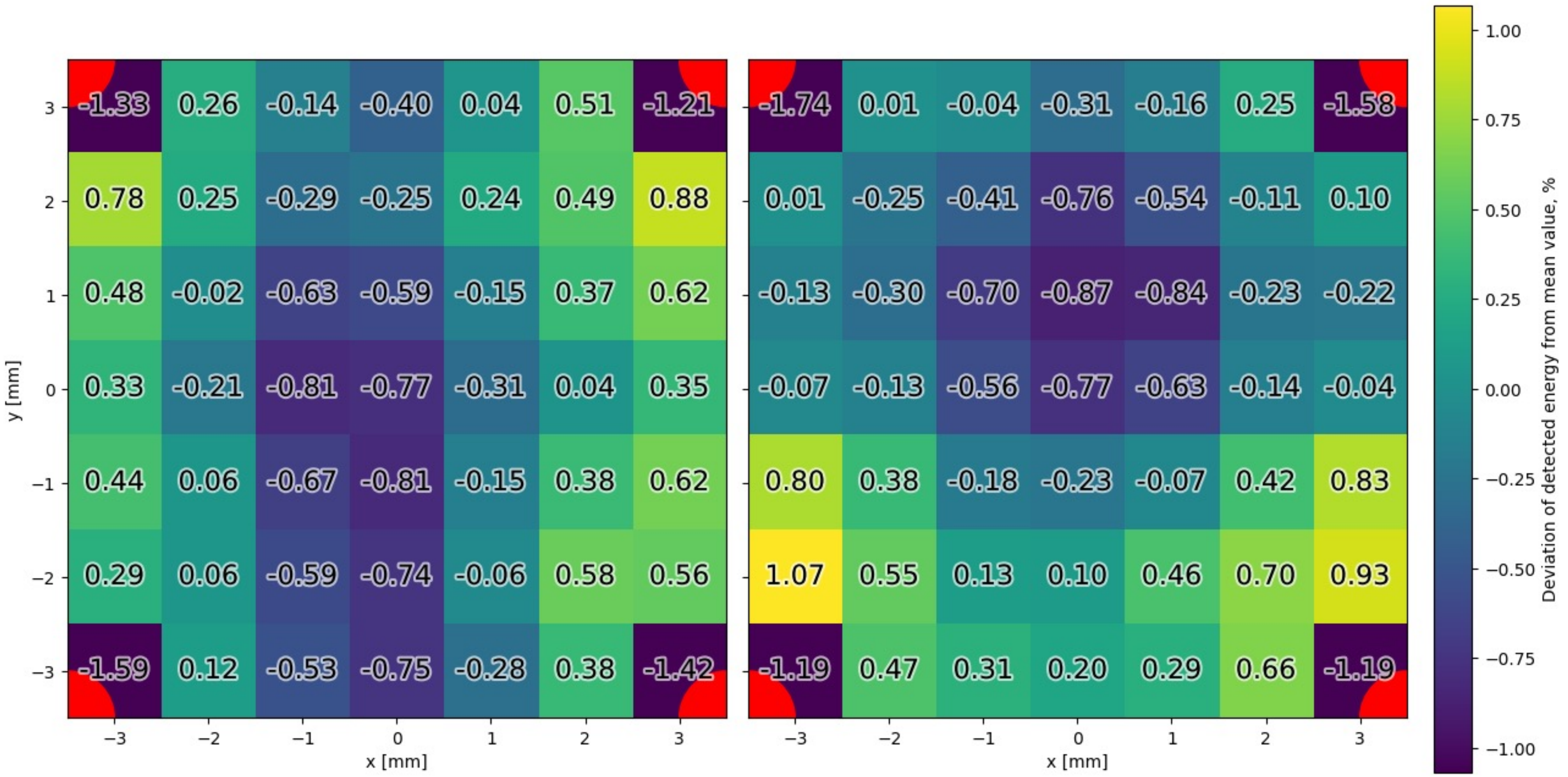
Impact on the constant term

Geant4 simulation of a full-size prototype (17 x 17 x 40 cm^3) with a mixture of $ZnWO_4$ (no grains) and sodium polytungstate

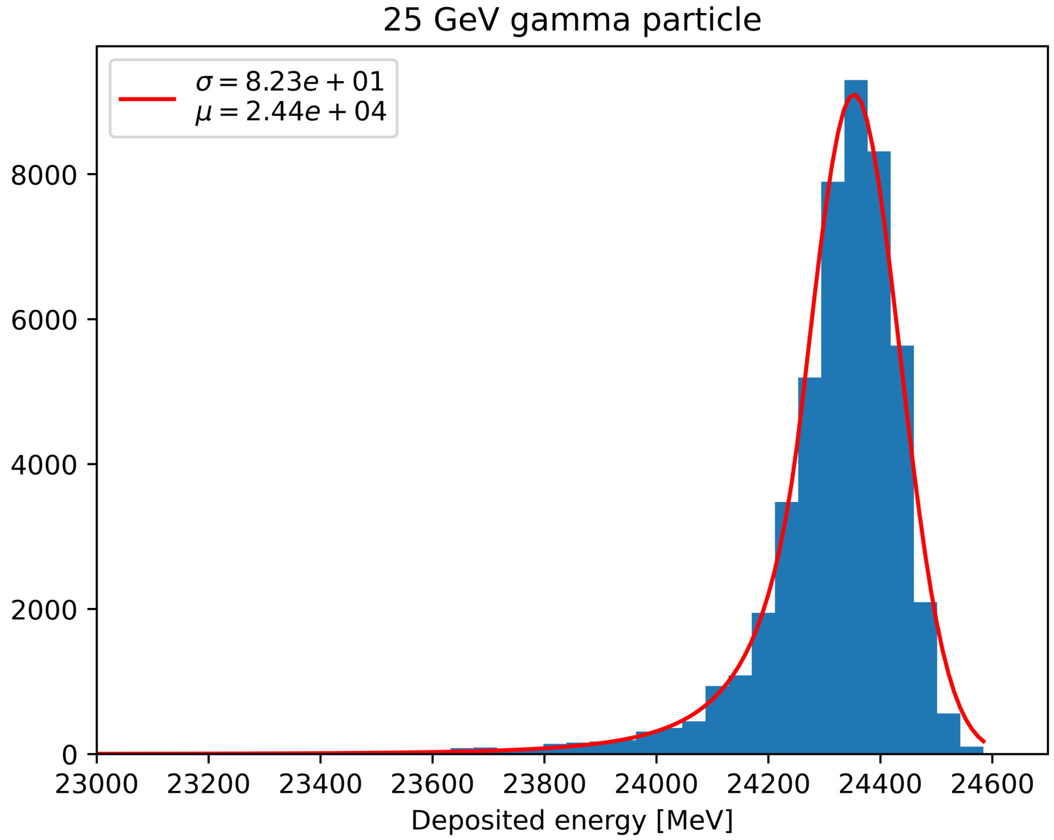
25 GeV γ



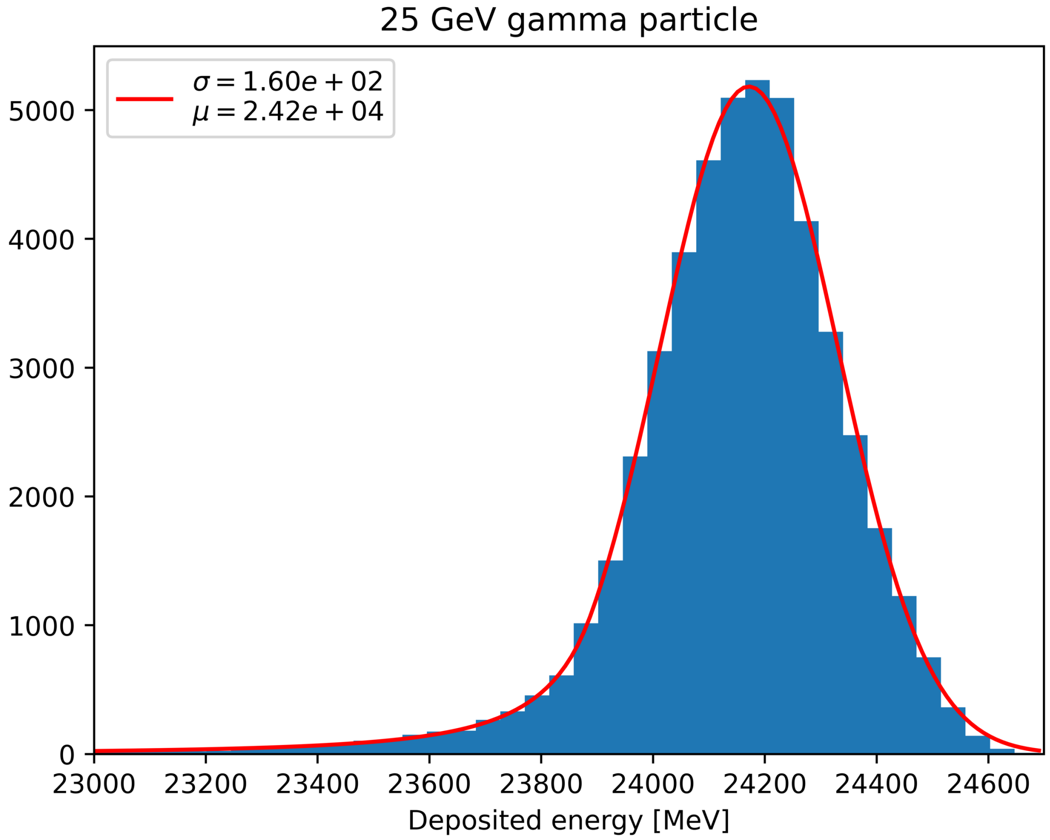
Deviation of the detected energy from mean value (%)



No uniformity simulated



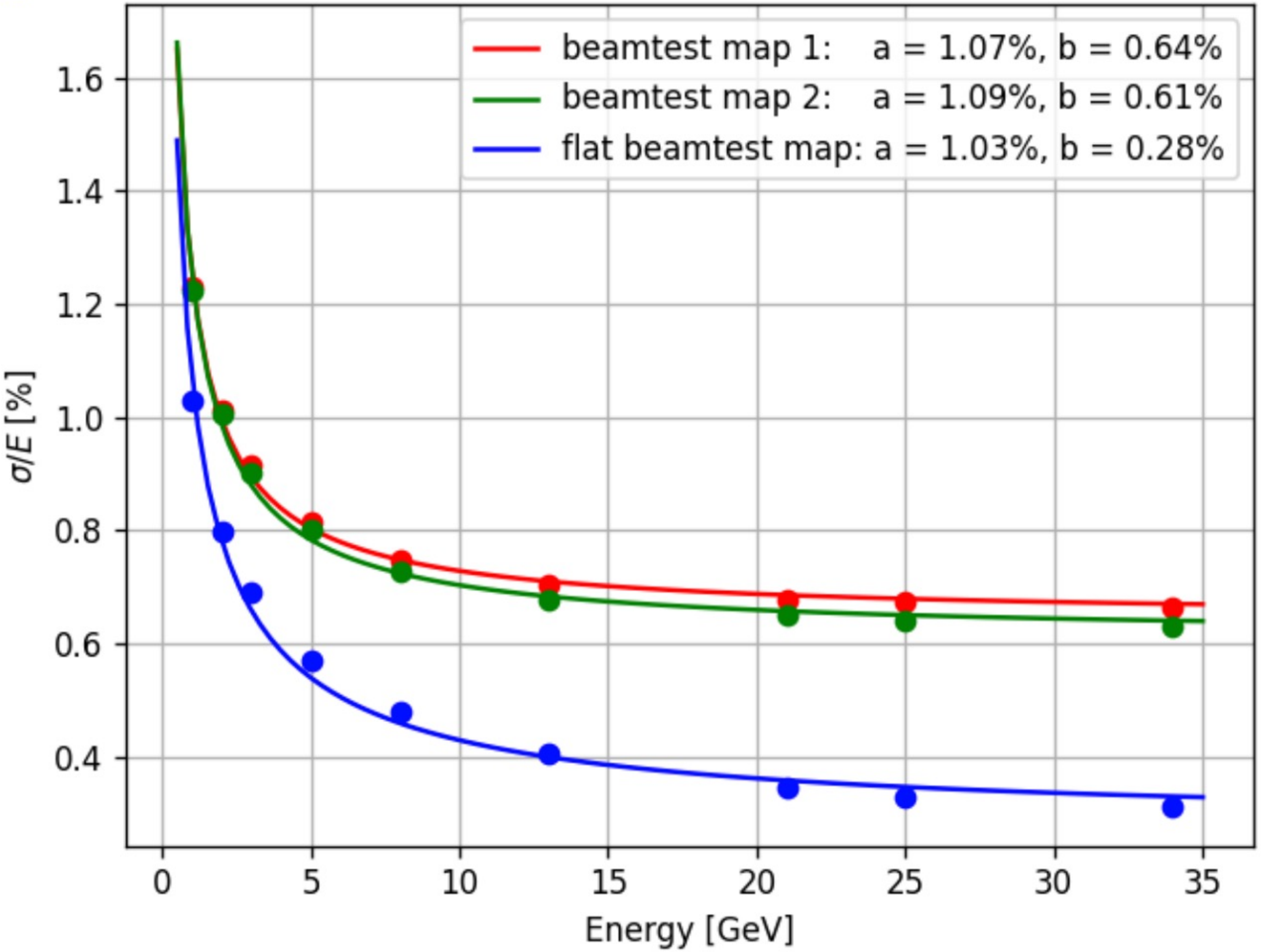
With map from the test beam



Constant term ~ 0.7 % (including the systematics from the pion model)

Energy resolution

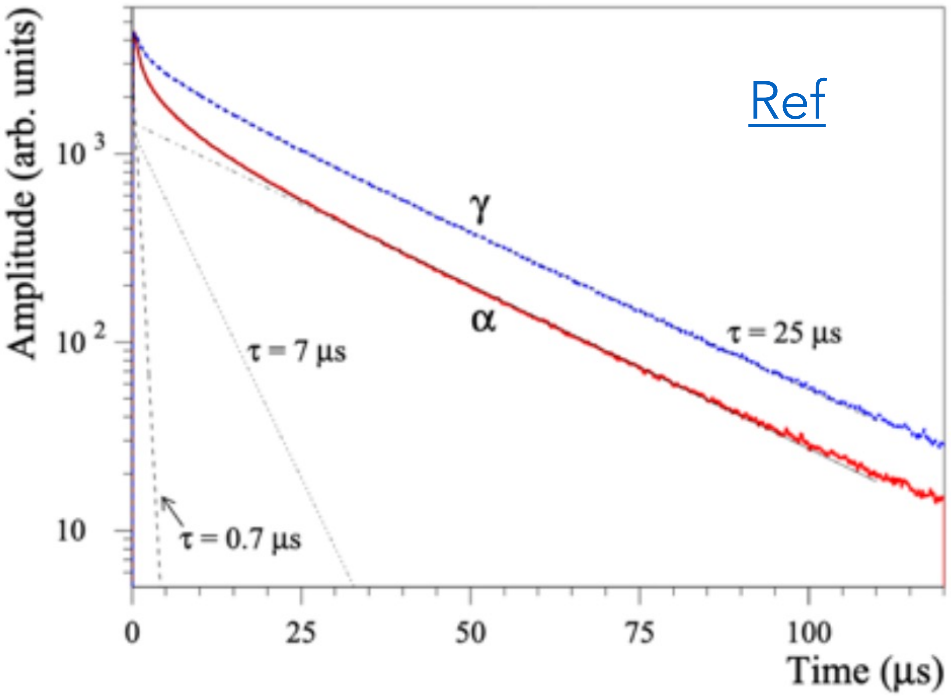
GRAiNITA internal



A word about pulse shape discrimination

$ZnWO_4$: clear difference between γ and α ()

Type of irradiation	Decay constants, μs		
	τ_1 (A_1)	τ_2 (A_2)	τ_3 (A_3)
γ ray	0.7 (2%)	7.5 (9%)	25.9 (89%)
α particles	0.7 (4%)	5.6 (16%)	24.8 (80%)



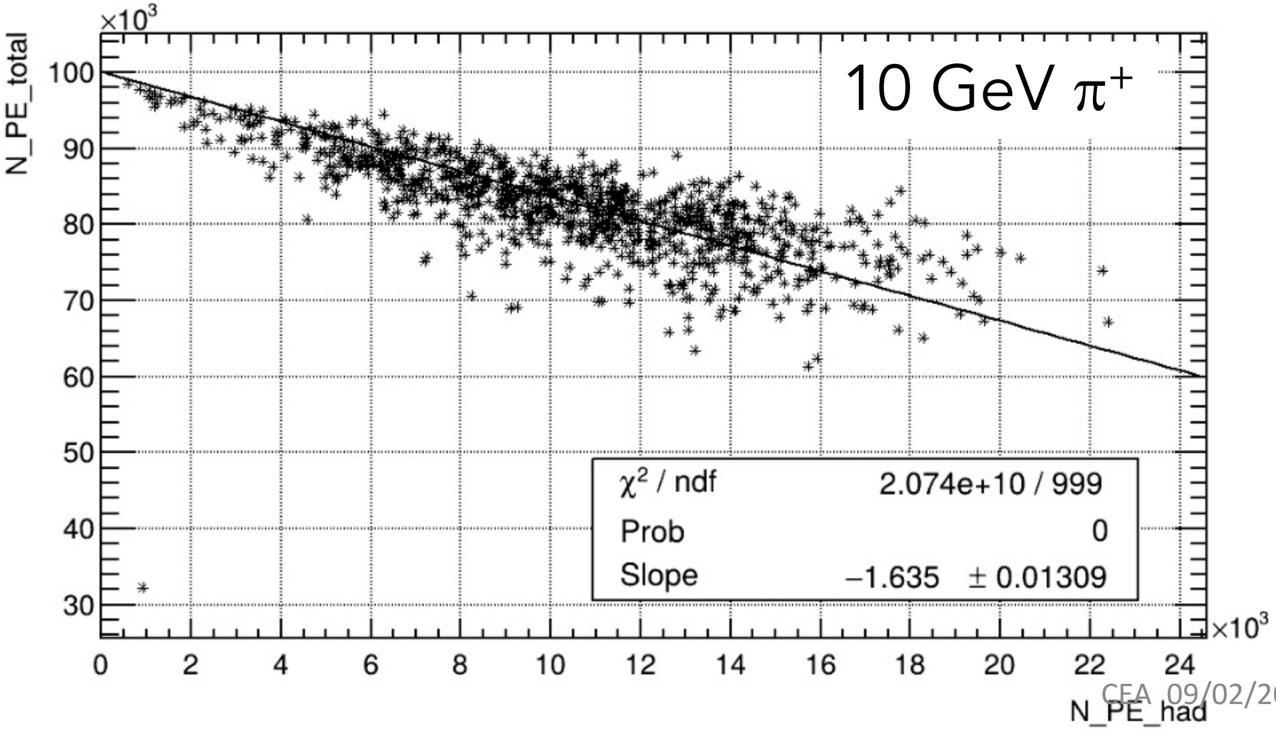
Can it be used to separate electromagnetic and hadronic components in a hadron shower ? (as Cerenkov vs scintillation do).

- Data taken with protons at the ALTO accelerator (energy from 10 to 20 MeV)

→ 4 sets of lifetime (electrons, low E protons, ‘high’ E proton, α), inputs to G4 optical model

- Demonstrated the ability to extract the electromagnetic fraction of the shower

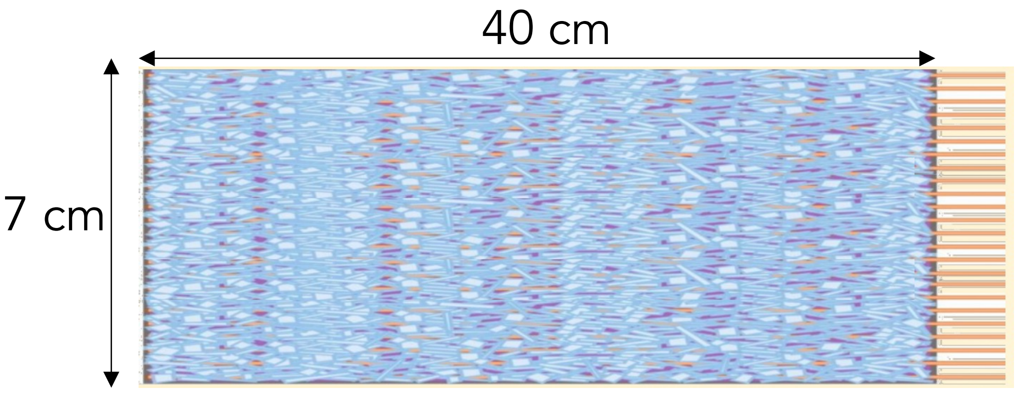
- → possibility to correct and thus improvement in the hadronic energy resolution



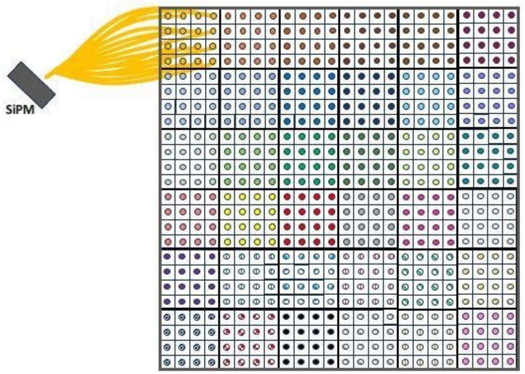
WIP

Towards a scale-one calorimeter module

Got a grant to build a full-size module demonstrator to assess all the components of the resolution



25 X0
(full containment of a 25 GeV elm shower)

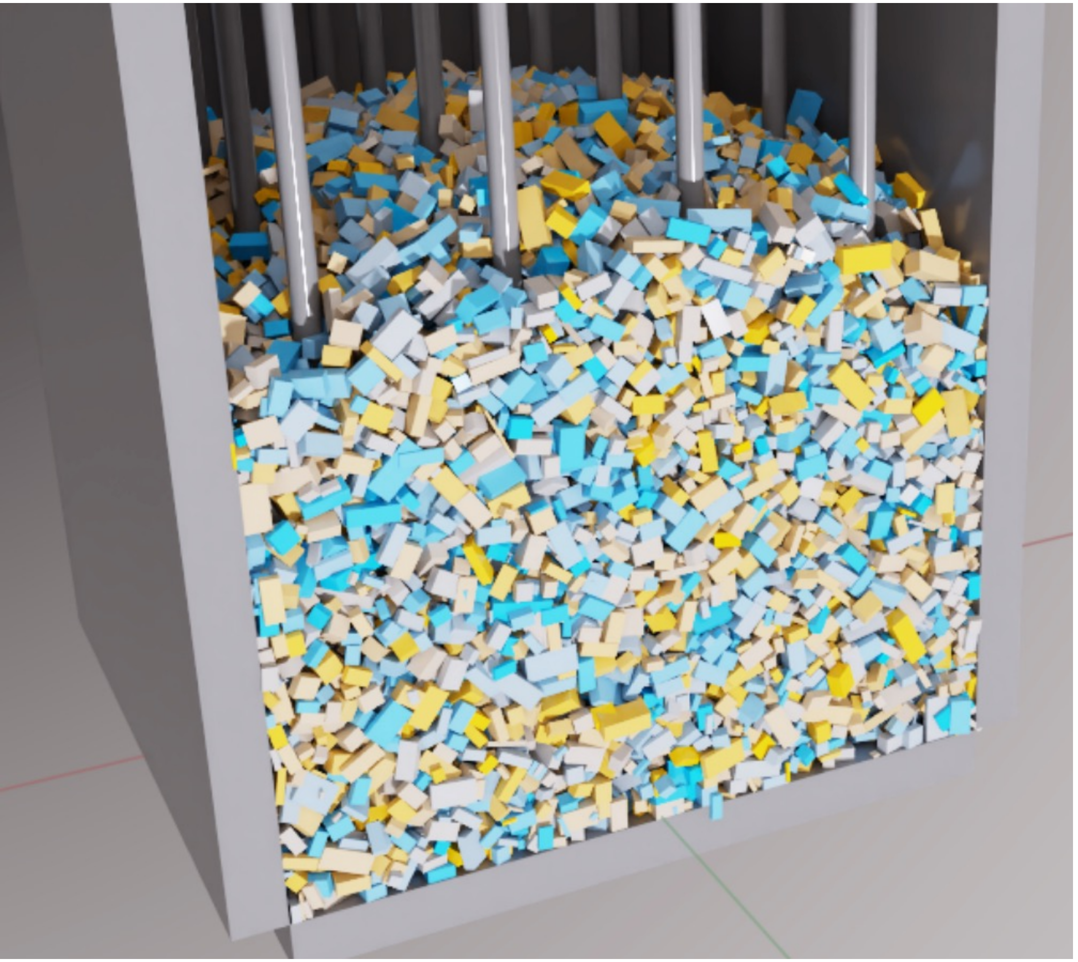


576 WLS fibres separated by 7mm (as in the small prototype) grouped in 16 fibres bundle coupled to 36 large-area SiPMs

Goal is to have a prototype built in 2028
→ test with cosmics and beams

Stay tuned

Quantify with a realistic simulation the effect of the grains.



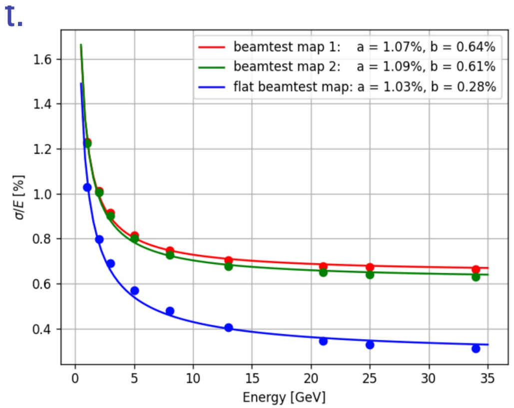
GRAiNITA is young !

Feb 2020, just before COVID

- **End of 2019, beg of 2020**: first G4 simulations
- **Spring 2021**: First test bench measurements with salt & comparison with G4 simulations
- **2022**:
  - very first measurements with $ZnWO_4$, WLS identification
  - start a collaboration with LPC-Clermont (Pulse Shape Discrimination , cosmic test bench)
  - Funding from IN2P3 for a small prototype
- **2023**: building the 16-channels prototype & cosmics rays test
- **2024**: test of the 16-channels prototype at CERN on μ/π test beam
- **2025:** ANR grant to build a scale-one module
- **2026**: start of the collaboration with CERN for the design of a calorimeter for FCCee

Conclusion and future

- Analysis of the test beam data:
  - confirms N_{PHE} value
  - constant term from non-uniformity ~ 0.7% (limitations due to the prototype size)

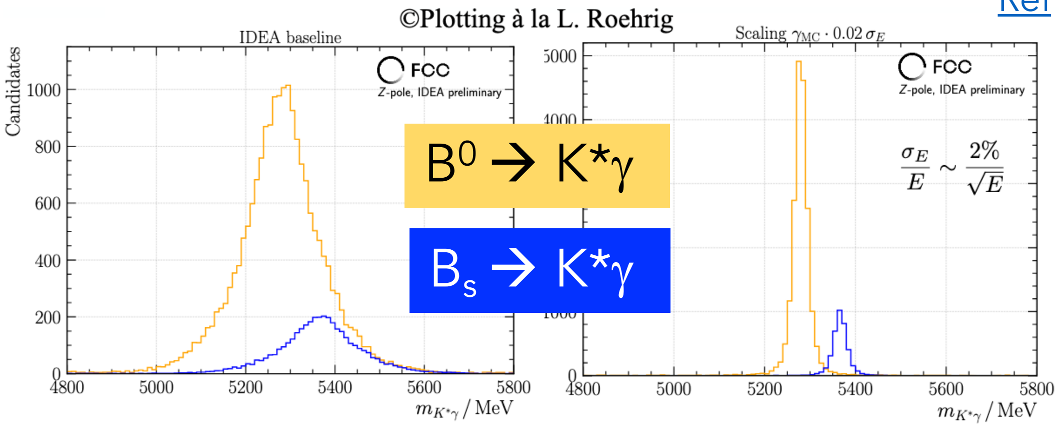


- Other (on-going) studies and tests:
  - heavy liquid
  - other crystals ($CaWO_4$, $Ca/PbWO_4$, …)
  - Mirror at the ends of the fibres

$$\frac{\sigma_E}{E} \sim \frac{12\%}{\sqrt{E}} \qquad \frac{\sigma_E}{E} \sim \frac{2\%}{\sqrt{E}}$$

- Pulse Shape Discrimination:
  - data with electrons and p (at ALTO@IJCLab : 12 MeV proton beam) recorded
  - Inputs to Geant4 has started

Ref

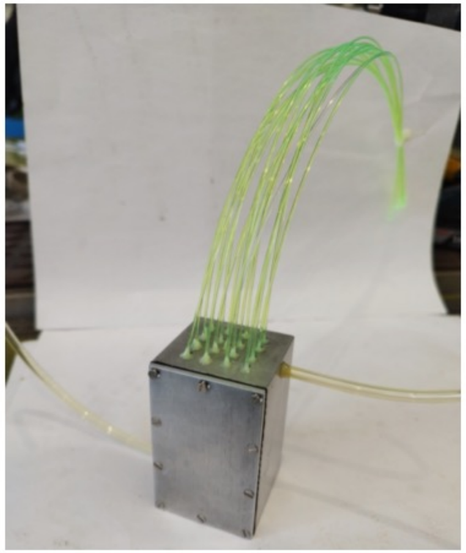


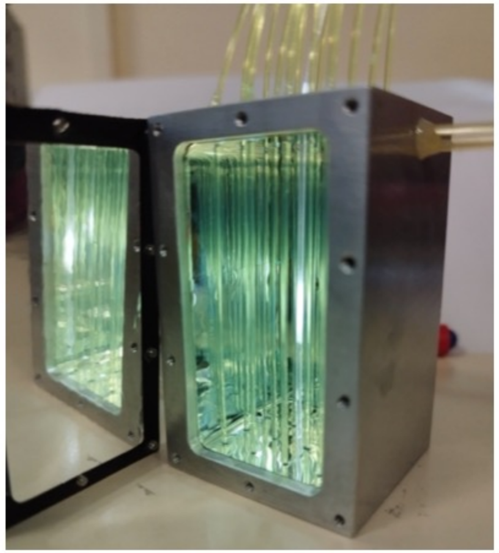
- Collaboration with CERN for the design of a calorimeter for FCCee

Backup slides

ZnWO4 or CaWO4 ?

We also have an alternative candidate: CaWO4

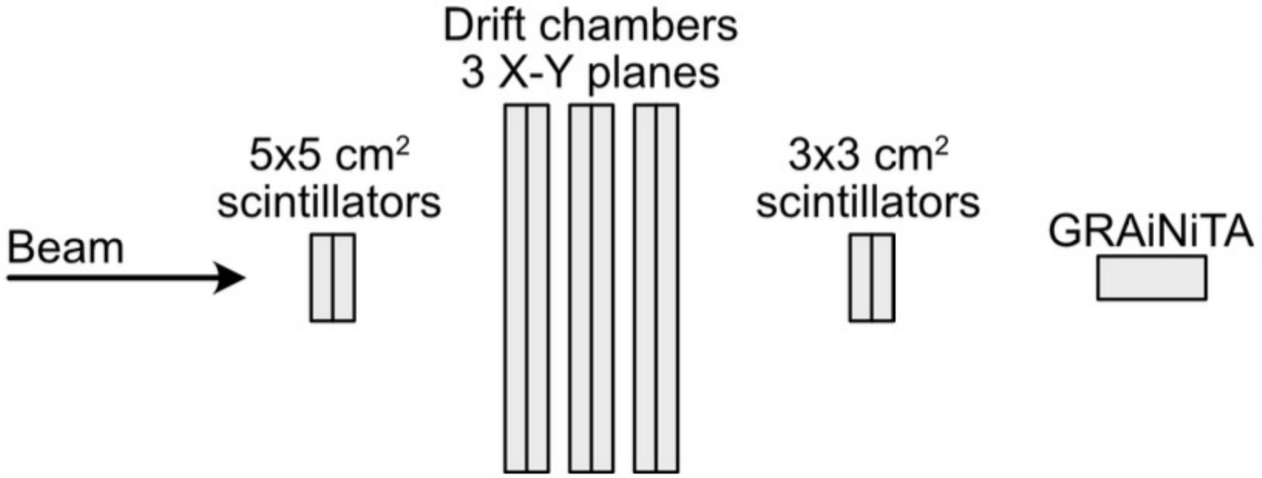


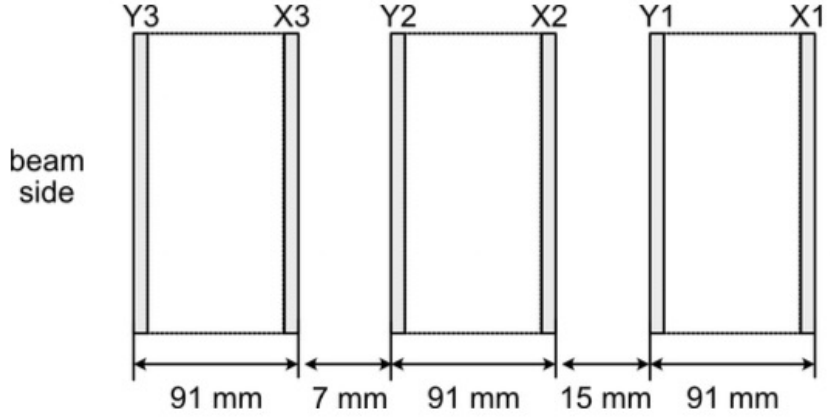


Same production technique (flux method)
Faster signal : 12.5 µs instead of 25 µs
Expect a good light yield, shifted to green → use Y11

Measured number of photo-electrons ~ 1.7 x ZnWO4 using cosmics …

…but density significantly lower (6.1 vs 7.6)

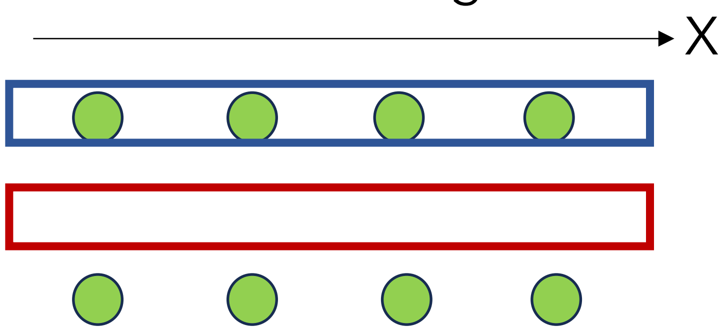

Drift chambers
3 X-Y planes
5x5 cm²
scintillators
3x3 cm²
scintillators
Beam
GRAiNiTA

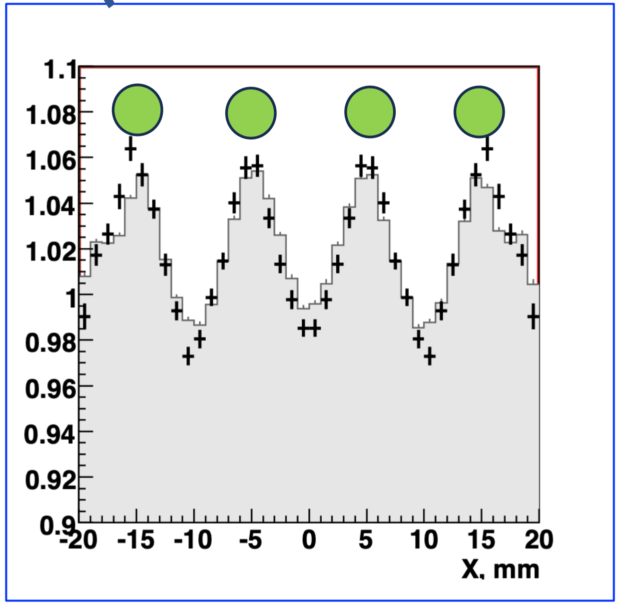

Y3
X3
Y2
X2
Y1
X1
beam
side
91 mm
7 mm
91 mm
15 mm
91 mm

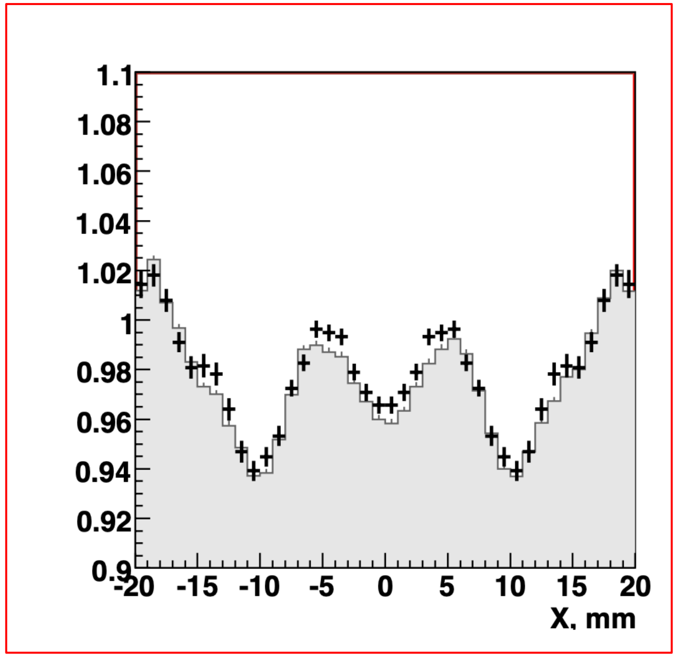
Principle of the method (LHCb calorimeter)

Beam Test Results of the LHCb Electromagnetic Calorimeter

Scan in two regions







Grey = simulation

~0.8% constant term for LHCb calorimeter